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Application of a 1-D Heat Budget Model to the Columbia River System

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APPLICATION OF A 1-D HEAT BUDGET MODEL TO THE COLUMBIA RIVER SYSTEM

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Executive Summary

In accordance with Section 303 of the Clean Water Act, the states of Oregon and Washington have identified portions of the main stem of the Columbia River from the International Border (Columbia River Mile 745.0) to the mouth at Astoria, Oregon and the Snake River from Anatone, Washington (Snake River Mile 168.0) to its confluence with the Columbia River (Figure 1) as water quality limited. This designation arises from an analysis of data by the State of Washington's Department of Ecology and the State of Oregon's Department of Environmental Quality showing these waters do not meet water quality standards during all or part of the year. Under Section 303 (d) of the Clean Water Act, States are required to establish Total Maximum Daily Loads for pollutants at a level that implements the applicable standards for water temperature. The goal of Columbia River Temperature Assessment is to provide support for the priority-setting phase of the TMDL process by assessing the impacts of the principal sources of thermal energy. The central product of the temperature assessment was the development of a mathematical model that predicts temperature along the Columbia River from the Grand Coulee Dam to the Bonneville Dam and along the Snake River from its confluence with the Grande Ronde River (Snake River Mile 168) to its confluence with the Columbia.

The mathematical model predicts average daily temperatures, specific to locations along the lengths of the Rivers, but averaged across the width and depth of the Rivers. Key elements of the model include the ability to expand the model geographically, an algorithm that quantifies the uncertainty of the modeled results, and a twenty-one year database of temperature and climate data. The model is based on the energy budget method and uses an efficient numerical solution technique that simplifies the characterization of model uncertainty. The energy budget method accounts for the exchange of heat with the atmosphere and the input of advected thermal energy from major tributaries and points sources.

The temperature assessment includes a summary of a biological study on salmon and the impacts of temperatures on their various life-stages.

Study Objectives

The objective of this study was to determine, for a given sequence of hydrology and meteorological conditions, the relative impacts of the operation of dams and reservoirs on the thermal energy budget and ambient temperature regime of the main stem Columbia and Snake rivers compared to the impact of thermal input from surface and groundwater inflows. The specific objectives were:

- Estimate the frequency with which daily-average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20^{o} C under existing conditions of river management and a representative record of river hydrology and meteorology

- Estimate the frequency with which daily-average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20^{o} C for the unimpounded condition. That is, the condition in which there are no dams in place below Grand Coulee on the Columbia and on the Snake below Lewiston, Idaho.

- Estimate the frequency with which daily-average water temperatures in the Columbia and Snake Rivers will exceed the benchmark of 20^{o} C under existing conditions of river management and with major tributaries and point sources constrained to maintain temperatures less than 16^{o} C.

- Characterize the uncertainty of these estimates for purposes of ultimately assessing the risks associated with potential management decisions in the Columbia and Snake rivers.

The benchmark of 20^{o} C was chosen because it is at water temperatures greater than this that adult salmon are at risk. While the benchmark does represent certain aspects of the physiological requirements

of salmonids, it is not viewed in the Report as a surrogate for water quality criteria or as part of an ecological risk analysis. The constraint of 16^{o} C on maximum temperatures in the tributaries was based on the State of Washington's water temperature criterion for tributaries classified as Class A (excellent). However, the use of the constraint was not meant to imply that tributaries had attained this criterion or would do so in the future. Rather it was used to evaluate what the relative impact of the tributaries on the thermal regime of the main stems might be under very favorable conditions.

Model Scenarios

Three scenarios were defined for purposes of achieving the objectives of the assessment. The scenarios were designed to characterize the temperature regimes under the following conditions:

1. All hydroelectric facilities in the study area in place

2. The Columbia River unimpounded from Grand Coulee Dam to Bonneville and the Snake River unimpounded from Snake River Mile 168 to the confluence with the Columbia River.

3. All hydroelectric facilities in place and the water temperature of major tributaries constrained to be equal to or less than contribute water temperatures equal to or less than 16 ^{o}C.

A 21-year record of actual meteorological and hydrologic data for the Columbia and Snake rivers was used to represent the environmental variability of the system for all scenarios and management of water quantity in the system was assumed to remain the same for all scenarios.

Results

The average frequency of daily-averaged temperature excursions above 20 ^{o}C increased monotonically from 0.0 at Grand Coulee Dam on the Columbia River to 0.16 at Bonneville Dam for the scenario representing existing conditions (all hydroelectric facilities in place. Corresponding values for average frequency of excursions for the unimpounded scenario were 0.0 to 0.03 from Grand Coulee Dam to Bonneville Dam. The average frequency of excursions for the scenario in which tributary temperatures were constrained to be equal to or less than 16 ^{o}C were essentially the same as the scenario for existing conditions.

For the Snake River, the average frequency of daily-averaged temperature excursions above 20 ^{o}C increased from its initial value of 0.16 at Snake River Mile 168 to 0.19 at Ice Harbor Dam for the scenario representing existing conditions (all hydroelectric facilities in place). The average frequency of excursions for the unimpounded scenario had an initial value of 0.16 at Snake River Mile 168, decreased slightly to 0.14 at Lower Granite Dam due to the influence of the Clearwater River, and then increased to 0.15 at Ice Harbor Dam. The average frequency of excursions for the scenario in which tributary temperatures were constrained to be equal to or less than 16 ^{o}C were reduced significantly at Lower Granite Dam, and only slightly Ice Harbor Dam as a result of the influence of the Clearwater River.

The impact of tributaries on the average frequency of daily-averaged temperature excursions is related directly to their size relative to the main stem Columbia and Snake rivers. For the geographical scope included in the analysis, only the Clearwater River in relation to the Snake River and the Snake River in relation to the Columbia River had a significant impact on the thermal regime of the respective main stems. The Snake River is the most significant tributary to the Columbia River in terms of its impact on the temperature regime. The Snake River contributes to increases in the frequency of temperature excursions above 20 ^{o}C for scenarios with dams in place as well as for scenarios for the unimpounded river. The Clearwater River provides cool water to the Snake and reduces the frequency of temperature excursions. Constraining the Clearwater River to water temperatures of 16 ^{o}C or less results in significant cooling of the Snake River.

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Conclusions

The following conclusions were drawn from the results:

- Structural changes in Columbia River downstream from Grand Coulee Dam and in the Snake River from its confluence with the Grande Ronde River to its confluence with the Columbia River near Pasco, Washington cause an increase in mean frequency of water temperature excursions above a daily-averaged water temperature of 20 ^{o}C relative to the unimpounded river. The structural changes are a result of the construction and operation of hydroelectric facilities on the Columbia and Snake rivers in the study area. This conclusion is based on a comparison of the mean frequency of temperature excursions for the system as presently configured and for the same system in the unimpounded condition. The unimpounded condition assumes there are no dams on the Columbia River below Grand Coulee and no dams on the Snake River below Lewiston, Idaho. The uncertainty in these estimates is approximately of the order of the estimated differences in the results. Improving both the systems and measurements models could reduce uncertainty. This could include improving the quality of water temperature observations, increasing the spatial coverage of required meteorological data and by studying the seasonal variations in certain terms of the heat budget, particularly the evaporation rate. However, the conclusion that construction and operation of the hydroelectric facilities have a greater impact on the thermal regime of the Columbia and Snake Rivers than does thermal input from most major tributaries would not be changed by the reduction in uncertainty.

- The impact of most advected sources, including tributaries, groundwater and point sources, on the cross-sectional daily-average water temperature of the main stem Columbia and Snake rivers in the study area is limited by their relatively small contribution of advected thermal energy. The exceptions to this are the impacts of the Clearwater River on the cross-sectional daily-average water temperature of the Snake River and that of the Snake River on the cross-sectional daily-average water temperature of the Columbia River.

- The objective of the analysis was to assess the relative impact of dams and tributaries on the temperature regime of the Columbia River from Grand Coulee Dam to Bonneville Dam and Snake River from its confluence with the Grande Ronde River (River Mile 168) to its confluence with the Columbia River. The impact of upstream inputs was limited to the characterization of initial temperature conditions at Grand Coulee Dam on the Columbia River and River Mile 168 on the Snake River. However, upstream inputs have an important role in the temperature regime of both rivers. In the Columbia River, construction of Canadian impoundments and the operation of Grand Coulee Dam have an important role in the temperature of the Columbia River at Grand Coulee Dam. For the Snake River, initial conditions near Anatone, Washington are such that the mean frequency of temperature excursions is approximately 0.15. This is due to structural changes to the natural river upstream from Anatone, Washington as well as to the time the river is exposed to high temperatures as it crosses the Snake River Plain. A larger geographical scope is needed to assess the basin-wide impacts of water management in both the Columbia and Snake rivers.

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CHAPTER 1: COLUMBIA RIVER SYSTEM AND STUDY OBJECTIVES

1.1 INTRODUCTION

The objective of the Clean Water Act (as amended by the Water Quality Act of 1987, Public Law 100-4) is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. Each state has developed standards for water quality that are used to judge how well the objectives of the Clean Water Act are being achieved. The water quality standards consist of the designated beneficial uses of the water and the water quality criteria necessary for achieving and maintaining the beneficial uses.

Under Section 303 of the Clean Water Act, states must identify waters for which effluent limitations, as required by Section 301, are not sufficient to implement established water quality standards. Oregon and Washington have identified portions of the main stem of the Columbia River from the International Border (Columbia River Mile 745.0) to the mouth at Astoria, Oregon, and the Snake River from Anatone, Washington, (Snake River Mile 168.9) to its confluence with the Columbia River as water quality limited (Figure 1-1). This designation arises from an analysis of data (Washington DOE, 1998; Oregon DEQ, 1998) showing these waters do not meet water quality standards during all or part of the year. Sources that may contribute to impairment of water quality in these segments of the Columbia and Snake rivers include the following:

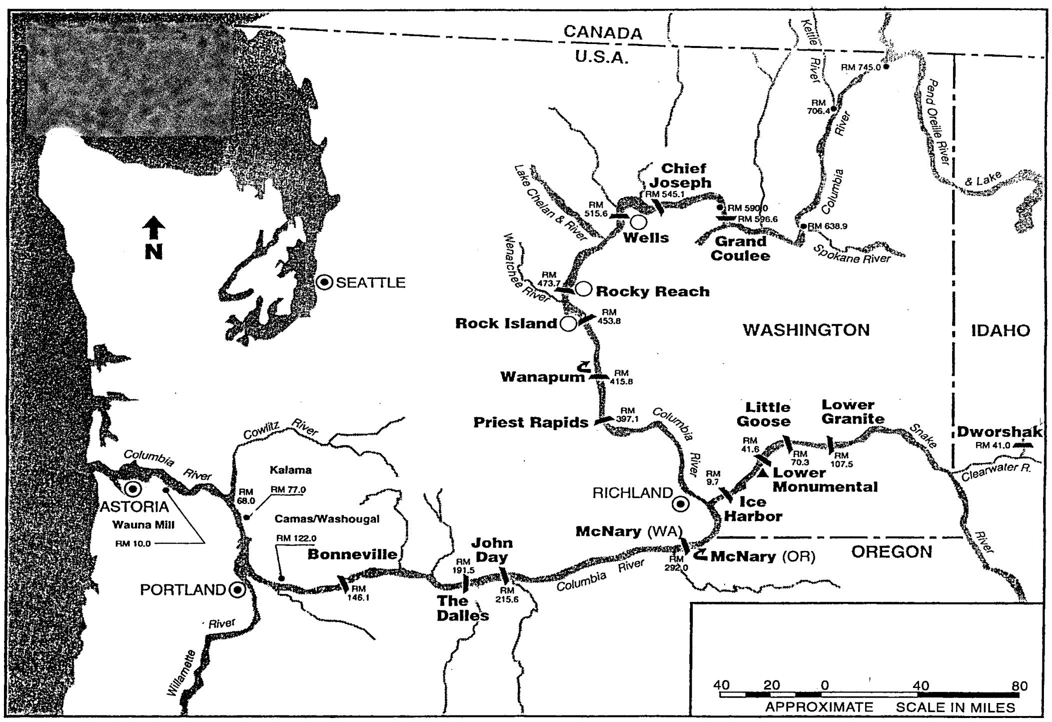

Figure 1-1. The Columbia and Snake rivers and associated hydroelectric projects in the study area.

- Construction of impoundments for hydroelectric facilities and navigational locks, which increase the time waters of the Columbia and Snake are exposed to high summer temperatures and change the system's thermal response time.
- Hydrologic modifications to the natural river system to generate electricity, provide irrigation water for farmlands, and facilitate navigation.

- Modifications of the watershed by agriculture and silviculture practices that reduce riparian vegetation, increase sediment loads, and change stream or river geometry.
- Operation of pulp and paper manufacturing facilities that discharge thermal energy and toxic substances, particularly dioxin.

After the water quality limited segments have been identified, priorities must be established for attaining water quality standards based on the severity of the pollution and the beneficial uses of the water body. Water temperature is one of the most frequently occurring constituents on Oregon's and Washington’s lists of water quality limited segments on the Columbia and Snake rivers. Segments of the Columbia and Snake rivers in the study area that are water quality limited for water temperature and for which the listing criteria require a Total Maximum Daily Load (TMDL) are given in Table 1-1.

Table 1-1. Parameter list for water quality limited segments of the Columbia and Snake River in Washington

State	Water Body Name	River Mile	Parameter	Action Needed
OR	Columbia River	146.1 – 191.5	Temperature	TMDL
OR	Columbia River	191.5 – 215.6	Temperature	TMDL
OR	Columbia River	215.6 – 292.0	Temperature	TMDL
OR	Columbia River	292.0 – 309.3	Temperature	TMDL
WA	Columbia River	290.5	Temperature	TMDL
WA	Snake River	139.6-0.0	Temperature	TMDL
WA	Snake River	168.0 – 139.6	Temperature	TMDL
WA	Columbia River	515.6	Temperature	TMDL
WA	Franklin D. Roosevelt Lake	596.6	Temperature	TMDL

When setting priorities for attaining established water quality standards for temperature, the first step is to assess the importance of sources that may significantly affect the thermal energy budget. Changes in the thermal energy budget of the Snake and Columbia rivers, relative to the natural unregulated river system, are due primarily to advected thermal energy from point sources, surface water, and ground water, as well as modification of river geometry and hydraulics due to the construction and operation of hydroelectric facilities. The goal of this work is to support the priority-setting phase of the TMDL process by assessing the impacts of the principal sources of thermal energy.

1.2 GEOGRAPHY, CLIMATE, AND HYDROLOGY OF THE COLUMBIA BASIN

Geography

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the states of Idaho, Oregon, Washington, and Wyoming. The Columbia River rises in the Rocky Mountain Trench and flows more than 400 miles through the rugged, glaciated mountains of southeastern British Columbia before it reaches the U.S.-Canada border near Castlegar, British Columbia. The Columbia River enters the United States from the Okanogan Highland Province, a mountainous area of Precambrian-early Paleozoic marine sediments. The Columbia crosses the western margin of the Columbia Basin—a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt—and flows south across the state of Washington. Near Pasco, Washington, and the confluence with the Snake River, the Columbia turns west, forms the border between Oregon and Washington, and flows more than 300 miles through the Casscade Mountain Range to the Pacific Ocean near Astoria, Oregon.

The headwaters of the Snake River are in Jackson Lake in the Teton Mountains of Wyoming at an elevation of 7,000 feet above sea level. The river flows west across the Snake Plain, which is also a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt. At the western edge of Idaho, it turns north and flows through a deeply incised canyon, emerging near Lewiston, Idaho. At Lewiston, the Snake joins the Clearwater River and flows west through the Palouse Country of eastern Washington, joining the Columbia near Pasco, Washington. Other major tributaries of the Snake in Idaho include the Bruneau, Owyhee, Boise, Payette, Weiser, and Salmon rivers.

Although the Snake River is the Columbia's largest tributary, other major tributaries include the Kootenai, Clark Fork-Pend Oreille, Spokane, Deschutes, and Willamette rivers. The Kootenai lies largely in Canada, but flows through western Montana, northern Idaho, and back into Canada before entering the Columbia below Lower Arrow Lake in British Columbia. The Clark Fork-Pend Oreille has its headwaters on the Continental Divide in Montana, flows through northern Idaho into Pend Oreille Lake and becomes the Pend Oreille River. The Pend Oreille River flows north into Canada before joining with the Columbia River. Major tributaries of the Clark Fork are the Flathead, Blackfoot, and Bitteroot rivers. The Spokane River begins in Lake Coeur d'Alene in Idaho and flows west through eastern Washington, entering the Columbia in Lake Franklin D. Roosevelt (Lake FDR). Both the Deschutes and Willamette rivers have their headwaters in Oregon; the Deschutes rises in central Oregon and flows north across lava flows of the Columbia Basalt, while the Willamette begins in the Cascade Mountains and flows west to the Willamette Valley, then north to join the Columbia near Portland, Oregon.

Climate

The climate of most of the Columbia River drainage is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely, depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while annual precipitation can exceed 100 inches per year in some of the mountainous regions of Canada.

Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100 ºF (37.8 ºC) for extended periods. Temperatures at higher elevations remain cooler. Winters are cold throughout the basin and heavy snow falls in the mountains. The snowpack accumulates throughout the winter months as a result of frequent passage of storm systems from the Pacific Ocean. Some of the snowpack is incorporated into the extensive system of glaciers in the basin; however, between the months of March and June, depending on elevation, much of the snowpack begins to melt. The resulting hydrograph is typical of a snowmelt regime.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all of the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing, and summer air temperatures are seldom above 100 ºF (37.8 ºC) for long periods. Average annual precipitation west of the Cascades is more than 40 inches in most areas. Precipitation recorded at coastal stations is typically higher. Below about 5,000 feet, most of the precipitation falls as rain, with 70 percent or more falling between October and March.

Hydrology

Although the hydrology of the Columbia River system has been modified by the construction of numerous hydroelectric, irrigation, flood control, and transportation projects, the hydrograph still has the characteristics of a snowmelt regime. Streamflows are low during the winter, but increase beginning in spring and early summer as the snowpack melts. Melting of the winter snowpack generally takes place in May and June, and streamflows increase until the snowpack can no longer support high flows. Flows then recede gradually during the summer and are derived from reservoir storage and from ground water recession into the fall and winter.

Occasionally, runoff from winter storms augments the base flow and can increase river discharge rapidly. This is particularly true of the Willamette River, which does not depend on the operation of other reservoirs in the Columbia River system. Rather, it is influenced more by rain and can reach flood stage even with flood control available from reservoirs within the Willamette River system.

Mean annual river discharges for key locations on the main stem Columbia and Snake River and selected tributaries are shown in Table 1-2.

1.3 WATER RESOURCES DEVELOPMENT WITHIN THE COLUMBIA RIVER BASIN

The Columbia River and its tributaries have been developed to a high degree. The only segment of the Columbia River above Bonneville Dam that remains unimpounded is the Hanford Reach between Priest Rapids Dam (Columbia River Mile 397.1) and the confluence with the Snake River (Columbia River Mile 324.3). The 11 main stem hydroelectric projects in the United States (Table 1-3), from Grand Coulee Dam to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head available in this segment of the Columbia River main stem. Hydroelectric and flow control projects on the main stem of the Columbia River and its tributaries in Canada have resulted in significant control of flow in the Upper Columbia and Kootenai River Basins. The Snake River is also nearly fully developed, with 19 dams on the main stem and a number of impoundments on its tributaries.

Table 1-2. Mean annual discharges at selected sites on the main stem Columbia and Snake Rivers

Station Name	Gage #	Station Location		Period of Record	Average Flow (cfs)
		Latitude	Longitude		
Snake River near Anatone, Washington	13334300	46° 05'50"	116° 58'36"	1958-1995	34800
Tucannon near Starbuck, Washington	13344500	46°30'20"	118° 03'55	1914-1996	176
Palouse River near Hooper, Washington	13351000	46°15'02"	118° 52'55	1898-1996	588
Snake River below Ice Harbor Dam	13353000	46°15'02"	118° 52'55"	1913-1992	53400
Columbia River at the International Boundary	12399500	49° 00'03"	117° 37'42"	1938-1996	99200
Columbia River at Grand Coulee	12436500	47° 57'56"	118° 58'54"	1923-1996	108200
Columbia River at Bridgeport, Washington	12438000	48° 00'24"	119° 39'51"	1952-1993	110200
Okanogan River at Malott, Washington	12447200	48° 16' 53"	119° 42' 12"	1965-1996	3050
Methow River near Pateros, Washington	12449950	48° 04' 39"	119° 59' 02"	1959-1996	1560
Columbia River below Wells Dam	12450700	47° 56'48"	119° 51'56"	1968-1996	109400
Columbia River at Rocky Reach Dam	12453700	47° 31' 28"	120° 18'04"	1961-1996	113200
Wenatchee River at Monitor, Washington	12462500	47° 29' 58"	120° 25' 24”	1962-1996	3250
Columbia River below Rock Island Dam	12462600	47° 19'57"	120° 04'48"	1961-1996	116300
Crab Creek near Moses Lake, Washington	12467000	47° 11' 22"	119° 15' 53"	1942-1996	63
Columbia River below Priest Rapids Dam	12472800	46° 37'44"	119° 51'49"	1918-1996	118400
Walla Walla River at Touchet, Washington	14018500	46° 01' 40"	118° 43' 43"	1951-1996	568
John Day River at McDonald Ferry, Oregon	14048000	45° 35' 16"	120° 24' 30"	1904-1996	2080
Deschutes River at Moody, near Biggs, Oregon	14103000	45° 37' 20"	120° 54' 54"	1907-1996	5800
Columbia River at the Dalles	14105700	45° 36'27"	121° 10'20"	1878-1996	191000

Table 1-3. Hydroelectric projects on the main stem Columbia and Snake rivers included in the scope of the analysis

Project	River Mile	Start of Operation	Generating Capacity (megawatts)	Storage Capacity (1000s acre-feet)
Grand Coulee	596.6	1942	6,494	8,290
Chief Joseph	545.1	1961	2,069	588
Wells	515.8	1967	774	281
Rocky Reach	473.7	1961	1,347	440
Rock Island	453.4	1933	622	132
Wanapum	415.8	1963	1,038	710
Priest Rapids	397.1	1961	907	231
McNary	292.0	1957	980	1,295
John Day	215.6	1971	2,160	2,294
The Dalles	191.5	1960	1,780	311
Bonneville	146.1	1938	1,050	761
Lower Granite	107.5	1975	810	474
Little Goose	70.3	1970	810	541
Lower Monumental	41.6	1969	810	351
Ice Harbor	9.7	1962	603	400

These dams and reservoirs serve many purposes, including irrigation, navigation, flood control, municipal and industrial water supply, recreation, and hydroelectric power generation. There are approximately 7 million acres of irrigated farmlands in the Columbia River Basin, including 3.3 million acres in Idaho, 0.4 million acres in Montana, 1.9 million acres in Washington, and 1.3 million acres in Oregon (Bonneville Power Administration et al., 1994). The system has the capacity for generating more than 20,000 megawatts of hydroelectric energy, and slack-water navigation now extends more than 460 river miles from the mouth at Astoria, Oregon, to Lewiston, Idaho.

In the United States, federal agencies, private power companies, and public utility districts own the dams in the Columbia River Basin. The Columbia Treaty between the United States and Canada governs transboundary issues related to the operation of dams and reservoirs on the Columbia River system in Canada.

1.4 ROLE OF TEMPERATURE IN WATER QUALITY

For the Columbia and Snake rivers in Washington, Chapter 173-201A-030 (2) (b) of the Washington Administrative Code (WAC) defines characteristics uses as the following:

(i) Water supply (domestic, industrial, agricultural).

(ii) Stock watering.

(iii) Fish and shellfish:
Salmonid migration, rearing, spawning, and harvesting.
Other fish migration, rearing, spawning, and harvesting.

(iv) Wildlife habitat.

(v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).

(vi) Commerce and navigation.

The characteristic uses for the segments of the Columbia River in Oregon, as defined in the Oregon Administrative Rules (OAR) Chapter 340-041, are similar to those of Washington.

Water quality in the main stem Columbia and Snake rivers is sufficient to protect many of these beneficial uses. An important exception is that of salmonid migration, rearing, spawning, and harvesting. According to the Independent Scientific Group (1996), 200 distinct anadromous stocks returned several million adult salmon and steelhead to the Columbia River prior to development of the basin. Of these stocks, 69 have been identified as extinct and 75 others are at risk of extinction in various parts of the basin. The Independent Scientific Group concluded that the "development of the Columbia River for hydropower, irrigation, navigation and other purposes has led to a reduction in both the quantity and quality of salmon habitat, and most critical, a disruption in the continuum of that habitat."

Water temperature is an important water quality component of habitat for salmon and other cold water organisms in the Columbia and Snake rivers. The criterion for water temperature (Chapter 173-201A WAC and Chapter 340-041 OAR) in the main stem Columbia River from the mouth to Priest Rapids Dam (R.M. 397.1) and Snake River from the mouth to its confluence with the Clearwater River (R.M. 139.3) is that temperature shall not exceed 20 ^{o}C (60 ^{o}F) due to human activities. For the Columbia River from Priest Rapids Dam (R.M. 397.1) to Grand Coulee Dam (R.M. 596.6), the criterion for water temperature is that the temperature shall not exceed 18 ^{o}C (64.4 ^{o}F) due to human activities.

These criteria were developed specifically to protect cold-water aquatic life, including salmon and steelhead, in the Columbia and Snake rivers. Salmonids evolved to take advantage of the natural cold, freshwater environments of the Pacific Northwest. Temperature directly governs their metabolic rate and directly influences their life history. Natural or anthropogenic fluctuations in water temperature can induce a wide array of behavioral and physiological responses in these fish. These fluctuations may lead to impaired functioning of the individual and decreased viability at the organism, population, and species level. Feeding, growth, resistance to disease, successful reproduction, sufficient activity for competition and predator avoidance, and successful migrations are all necessary for survival.

Temperature preferences for five critical life stages of the salmonids found in the Columbia River system are listed in Table 1-4. Appendix A contains more detailed information on the preference ranges and effects of temperature on these fish. Additional information can be obtained from two recent EPA-sponsored reports: (1) *A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon* (1999) by Dale A. McCullough, and (2) *Perspectives on Temperature in the Pacific Northwest's Fresh Waters* (1999) by Charles C. Coutant.

1.5 IMPACTS OF WATERSHED DEVELOPMENT ON WATER TEMPERATURE

Once the water quality limited segments have been identified, Section 303 (d) of the Clean Water Act requires that each state establish a priority ranking determining the severity of the pollution and the uses of the water. One of the first steps is to assess the problems associated with a given water quality parameter. The purpose of an assessment is to identify the sources for the water quality parameter of concern.

Table 1-4. Summary of temperature preference ranges (^oC) for five critical life stages of seven salmonid species (from Appendix A)

	Adult Migration ^0C	Spawning ^0C	Incubation ^0C	Rearing ^0C	Smoltification Out-migration ^0C
Spring Chinook Salmon	3.3 - 13.3	5.6 - 14.4 5.6 - 12.8	5 - 14.4 4.5 - 12.8	10 - 12.8 10 - 14.8	3.3 - 12.2
Summer Chinook Salmon	13.9 - 20	5.6 - 14.4 6.1 - 18	5 - 14.4	10 - 12.8	NA
Fall Chinook Salmon	10.6 - 19.4	10 - 12.8 10 - 16.7 5.6 - 13.9	10 - 12.8 10 - 16.7 5 - 14.4	12 - 14	4.5 - 15.5
Sockeye Salmon	7.2 - 15.6	10.6 - 12.2	4.4 - 13.5	10 - 12.8 12 - 14 11.2 - 14.6	2 - 10
Coho Salmon	7.2 - 15.6	4.4 - 9.4 7.2 - 12.8	4.4 - 13.3 4 - 6.5	11.8 - 14.6	12 - 15.5
Chum Salmon	8.3 - 15.6	7.2 - 12.8	4.4 - 13.3	10 - 12.8 11.2 - 14.6	NA
Steelhead/ Rainbow Trout	10 - 13	3.9 - 9.4 4.4 - 12.8	5.6 - 11.1	7.3 - 14.6	< 12
Cutthroat Trout	NA	6.1 - 17.2	NA	9.5 - 12.9	NA
Bull Trout	10 - 12	<9 - 10 4 - 10	2 - 4 4 - 6	4 - 4.5 fry 4 - 10 juv	NA

NA - Not available

The listing of water temperature by Oregon and Washington is based on analysis of data collected by state and federal agencies. These agencies include the Oregon Department of Environmental Quality (DEQ), the Washington State Department of Ecology (DOE) and the U.S. Army Corps of Engineers (USACE). An analysis of long-term records the USACE collected as part of the total dissolved gas monitoring study (McKenzie and Laenen, 1998) shows the frequency with which water temperatures have exceeded the water quality criterion at various locations on the Columbia and Snake rivers (Table 1-5).

Table 1-5. Frequency and average magnitude with which observed temperatures exceed Oregon's and Washington's water quality criterion at selected locations on the Columbia and Snake rivers. Observed temperatures are from the total dissolved gas monitoring program (McKenzie and Laenen, 1998)

Location	Exceeds Water Quality Criterion		Record Length
	Frequency	Magnitude	
Lower Granite Dam	0.15	2.04	5/30/88-9/17/96
Little Goose Dam	0.15	2.49	5/30/88-9/16/96
Lower Monumental Dam	0.18	2.10	5/29/88-9/17/96
Ice Harbor Dam	0.18	2.35	5/29/88-9/23/96
Wells Dam	0.10	0.87	4/18/93-9/2/97
Priest Rapids Dam	0.18	1.61	4/28/88-12/31/97
McNary Dam	0.17	1.65	4/2/85-12/31/97
John Day Dam	0.15	1.65	4/17/84-9/16/97
Bonneville Dam	0.14	1.39	4/3/86-11/2/97

Previous studies of the Columbia and Snake rivers (Davidson, 1964; Jaske and Synoground, 1970; Moore, 1969; Independent Scientific Group[1], 1996) have identified the construction and operation of hydroelectric facilities as having a major impact on the thermal regime of the Columbia and Snake rivers. Jaske and Synoground (1970) concluded that the construction of river-run reservoirs on the main stem of the Columbia River caused no significant changes in the average annual water temperature, but that the operation of Lake FDR, the reservoir behind Grand Coulee Dam, delayed the time of the peak summer temperature in the Columbia River at Rock Island Dam by about 30 days. Moore (1969) found that both Lake FDR and Brownlee Reservoir on the Snake River caused cooling in the spring and summer and warming in fall and winter. The Independent Scientific Group (1996) concluded that "mainstem reservoirs in the Snake and Columbia rivers have created shallow, slowly moving reaches of shorelines where solar heating has raised temperature of salmon rearing habitat above tolerable levels" and that changes in the thermal energy budget associated with the hydropower system in the Columbia and Snake rivers have resulted in conditions that are suboptimal or clearly detrimental for salmonids.

Surface and groundwater flows tributary to the Snake and Columbia rivers are also sources of advected thermal energy that have the potential for modifying the thermal energy budget of the main stem. Moore (1969) studied the impact of the Clearwater and Salmon rivers on the main stem Snake and the Kootenai and Pend Oreille rivers on the Columbia during 1967 and 1968. He found that the Clearwater and Salmon rivers cooled the Snake River during some of this period, but at no time did they produce a warming effect. Viewing the Snake as a tributary to the Columbia, Moore (1969) and Jaske and Synoground (1970) concluded that the advected thermal energy from the Snake River increased the temperature of Columbia River during the summer. Moore (1969) estimated that the maximum temperature increase was of the order of 1 ^{o}C during 1967 and 1968, while Jaske and Synoground (1970) estimated the annual thermal energy contribution of the Snake River to the Columbia River to be on the order of 4,000 megawatts. The Independent Scientific Group (1996) discusses temperature in the tributaries primarily as it relates to habitat in individual tributaries. The group concludes that high temperatures in the late summer and fall are detrimental to both juvenile and adult salmon in the main stem and tributaries, but does not discuss the impact of the tributaries on the thermal energy budget of the main stem.

The only significant permitted point source discharge of thermal energy to the Columbia and Snake rivers in the study area (Figure 1-1) is the Potlatch Corporation discharge to the Snake River at Snake River Mile 139 near the confluence of the Snake and the Clearwater rivers. The Potlatch facilities discharge approximately 130 megawatts of thermal energy to the Snake River. The Hanford Project discharged as much as 23,000 megawatts of thermal energy and had significant impacts on the temperature of the Columbia River (Jaske and Synoground, 1970; Moore 1969; Yearsley, 1969). However, this discharge was discontinued in the 1970s.

1.6 STUDY OBJECTIVES

For the segments of the main stem Columbia and Snake rivers included in the study area (Figure 1-1), the impacts of watershed development on the thermal energy budget are associated with the operation of dams and reservoirs and advected energy from tributaries, ground water, and point sources. The objective of this study is to determine, for a given sequence of hydrology and meteorological conditions, the relative impacts of the operation of dams and reservoirs on the thermal energy budget of the main stem Columbia and Snake rivers compared to the impact of thermal input from surface and ground water inflows. The specific objectives are to do the following:

- Estimate the frequency with which daily average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20 ^{o}C (68 ^{o}F) under existing conditions of river management and a representative record of river hydrology and meteorology.

[1] The Independent Scientific Group comprised nine experts in fishery sciences commissioned by the Northwest Power Planning Council to (1) perform an independent review of the science underlying salmon and steelhead recovery efforts and Columbia River Basin ecosystem health, and (2) develop a conceptual foundation that could form the basis for program measures and basinwide fish and wildlife management.

- Estimate the frequency with which daily average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20 ^{o}C (68 ^{o}F) with all dams on the Columbia River below Grand Coulee Dam in place and for the unimpounded condition with no dams in place below Grand Coulee on the Columbia and on the Snake below Lewiston, Idaho.

- Estimate the frequency with which daily average water temperatures in the Columbia and Snake Rivers will exceed the benchmark of 20 ^{o}C (68 ^{o}F) under existing conditions of river management and with major tributaries and point sources constrained to maintain temperatures less than 16 ^{o}C (60.8 ^{o}F).

- Characterize the uncertainty of these estimates for purposes of ultimately assessing the risks associated with potential management decisions in the Columbia and Snake rivers.

The benchmark of 20 ^{o}C (68 ^{o}F) was chosen because adult salmon are at risk when water temperatures are warmer. For example, Karr et al. (1998), used 20 ^{o}C (68 ^{o}F) as a benchmark, representing it as an upper incipient lethal water temperature for migrating salmon and steelhead. Based on a literature review, Karr et al. (1998) determined that 20 ^{o}C (68 ^{o}F) is the point where the zone of lower resistance starts for immigrating adult salmon and steelhead. Results from the Columbia River Thermal Effects study reported by Bonneville Power Administration et. al. (1994) show that 20 ^{o}C (68 ^{o}F) is the water temperature where the zone of lower resistance starts for immigrating adult salmon and steelhead. At water temperatures higher than 21.1 ^{o}C (70 ^{o}F), salmonids are in a lethal range where the time it takes to kill the fish declines rapidly. More detailed information on temperature requirements for several species of salmonids is contained in Appendix A.

Although the benchmark does represent certain aspects of the physiological requirements of salmonids, this report does not view it as a surrogate for water quality criteria or as part of an ecological risk analysis. Washington's water quality standard is based on an instantaneous value. An ecological risk analysis would have to consider both the timing and magnitude of temperature changes. Although these issues are not specifically considered in this assessment, they may be included in future analyses of water temperature in the Columbia and Snake rivers.

The constraint of 16 ^{o}C (60.8 ^{o}F) on maximum temperatures in the tributaries was based on Washington's water temperature criterion for tributaries classified as Class A (excellent). The use of the constraint, however, was not meant to imply that tributaries had attained this criterion or would do so in the future; rather, it was used to evaluate what the relative impact of the tributaries on the thermal regime of the main stems might be under very favorable conditions.

A one-dimensional mathematical model of the thermal energy budget that simulates daily average water temperature under conditions of gradually varied flow is used to address the specific objectives described above. Models of this type have been used to assess water temperature in the Columbia River system for a number of important environmental analyses. The Federal Water Pollution Control Administration (Yearsley, 1969) developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River Thermal Effects Study. The Bonneville Power Administration et al. (1994) used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the System Operation Review, and Normandeau Associates (1999) used a one-dimensional model to assess water quality conditions in the Lower Snake River for the U.S. Army Corps of Engineers.

A one-dimensional model of daily average temperatures is appropriate for answering basic questions on how watershed development effects water temperature. Important issues associated with water temperature in the main stem Columbia and Snake Rivers for which this type of model is not appropriate include the following:

- Instantaneous temperatures: The water quality standards for the Columbia and Snake rivers in both Oregon and Washington are written in terms of instantaneous temperatures. The model used for this analysis does not simulate instantaneous water temperatures. Therefore, the model results cannot be compared directly to the criteria for water temperature established by the water quality standards of Oregon and Washington.

- Lateral and vertical variations in water temperature: The thermal energy budget model simulates the daily, cross-sectional averaged temperature. Important spatial dimensions of the lotic ecosystem (Independent Scientific Group, 1996) are the riverine (longitudinal), riparian (lateral) and hyporheic (vertical habitat below the river channel). Development of the hydropower system has caused significant changes to the thermal regimes in all these dimensions. The one-dimensional thermal energy budget model results can be used only to characterize the water temperatures in the riverine or longitudinal dimension of habitat. The model results correspond approximately to the state variable, "thalweg temperature," used by the Independent Scientific Group (1996).

- Unsteady flow: The model uses the methods of gradually varied flow to characterize river hydraulics. The gradually varied flow model may not be appropriate for highly transient flow conditions such as storm or very rapid snowmelt events.

- Strong longitudinal temperature gradients: The model assumes that dispersion and longitudinal turbulent diffusion can be neglected. Diffusion-like processes will be important when

  $$K_x/UL > 1$$

  where

  K_x = coefficient of longitudinal dispersion or eddy diffusivity

  U = river speed in the longitudinal direction

  L = a characteristic longitudinal distance

  Longitudinal dispersion is generally of great importance for one-dimensional models. Experimental values of the longitudinal dispersion coefficient in rivers and estuaries, reported in Fischer et al. (1979), vary from approximately 30 feet^2/second to 15,000 feet^2/second in rivers and from 100 feet^2/second to 15,000 feet^2/second in estuaries. Assuming the largest value of the dispersion coefficient (15,000 feet^2/second) and a river velocity of 1.0 foot /second implies a characteristic length of approximately 3 miles. To analyze conditions in the Snake and Columbia rivers when strong cross-sectionally averaged longitudinal gradients were important and scales on the order of 3 to 10 miles were of interest, it would be necessary to consider including diffusion-like processes in the model. The analysis described in this report did not include any impacts with scales of less than 3 to 10 miles.

CHAPTER 2: TEMPERATURE MODEL THEORY AND FORMULATION

2.1 THERMAL ENERGY BUDGET METHOD AND FORMULATION

Base Equations

The thermal energy budget method is a useful concept for simulating temperatures in aquatic environments. Concern about the impact of reservoir operations on water temperature and aquatic ecosystems motivated early applications of the method (Burt, 1958; Delay and Seaders, 1966; Raphael, 1962; Edinger et al., 1974). Prior to the passage of the Clean Water Act, numerous studies of Electric Power Industry thermal discharges were also performed using the energy budget method (Edinger et al., 1974). Brown (1969, 1970) applied the method to simulating stream temperature increases resulting from the removal of riparian vegetation during logging operations. Recent applications of the energy budget method have focused on water quality planning issues related to reservoir operations (Cole and Buchak, 1995; Normandeau Associates, 1999), watershed management (Bonneville Power Administration et al., 1994, Foreman et al., 1997; Risley, 1997; Rishel et al., 1982; Sinokrot and Stefan, 1993) and fisheries habitat enhancement (Bartholow, 1989; Theurer et al., 1984).

Thermal energy budget models for aquatic ecosystems are developed either in an Eulerian frame of reference, in which the reference system is fixed in space and through which the water flows, or a Lagrangian frame of reference, in which the reference system moves with the fluid. The one-dimensional thermal energy model for estimating the state variable, water temperature, stated in terms of the Eulerian viewpoint and assuming there is no longitudinal dispersion is as follows:

$$\rho C_p A_x \frac{\partial T}{\partial t} + \rho C_p \frac{\partial (QT)}{\partial x} = w_x H_{net} + S_{adv} + w_T \tag{1}$$

where

Δ = the density of water, kg/meter^3

C_p = the specific heat capacity of water, kcal/deg C/kg

A_x = the cross-sectional area of the river at the distance, x, meter^2

T = the true water temperature, ^oC

Q = the river flow rate, meter^3/second

w_x = the width of the river at the distance, x, meters

H_{net}= the heat flux at the air-water interface, kcal/meter^2/second

S_{adv} = the heat advected from tributaries and point sources, kcal/meter/second

w_T = a random water temperature forcing function, $\sim N(0, E_Q(t))$

x = the longitudinal distance along the axis of the river, meters

t = time

In the Lagrangian frame of reference, the systems model for estimating the water temperature, using the energy budget method and assuming no longitudinal dispersion, is given by

$$\rho C_p A_x \frac{dT}{dt} = w_x H_{net} + S_{adv} + w_T \tag{2}$$

where the symbols are as previously defined.

Equations 1 and 2 are the state-space system equations for water temperature in the Eulerian and Lagrangian frames of reference, respectively. Water temperature measurements also provide an estimate of the system state. The observation model for water temperature at the kth time interval is given by (Gelb et al., 1974)

$$Z_k = H_k T_k + v_k \tag{3}$$

where

Z_k = the measured value of the water temperature, ^oC

H_k = the measurement matrix,

v_k = the measurement error, $\sim N(0, E_R)$

E_R = the variance of the measurement error, v_k

Heat Exchange Across the Air-Water Interface

Heat exchange across the air-water interface is generally the major source of thermal energy for lakes, rivers, and reservoirs. As is the case for the applications described above, this study assumes the net exchange of thermal energy, H_{net}, across the air-water interface can be described by

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) +/- H_{evap} +/- H_{cond} - H_{back} \tag{4}$$

where

H_{net} = Net heat exchange across the air-water interface, kcal/meter^2/second

H_s = Shortwave solar radiation, kcal/meter^2/second

H_{rs} = Reflected shortwave solar radiation, kcal/meter^2/second

H_a = Longwave atmospheric radiation, kcal/meter^2/second

H_{ra} = Reflected atmospheric radiation, kcal/meter^2/second

H_{evap} = Evaporative heat flux, kcal/meter^2/second

H_{cond} = Conductive heat flux, kcal/meter^2/second

H_{back} = Blackbody radiation from the water surface, kcal/meter^2/second

The specific form for each of the terms in the heat budget formulation (Equation 4), as used in this and most other studies involving the energy budget method, is based on a compilation of heat budget studies by Wunderlich and Gras (1967). Chapra (1997) and Bowie et al. (1985) also have comprehensive discussions of each of the terms in Equation 4 adapted from Wunderlich and Gras (1967). From the work of Wunderlich and Gras (1967), individual elements of the heat budget are given by

Shortwave (Solar) Radiation

$$(H_s - H_{rs}) = F(M, *, D_y) \qquad (5)$$

where

M = the latitude of the site

$*$ = the declination of the sun at the site

D_y = the day of the year

Longwave (Atmospheric) Radiation

$$(H_a - H_{ra}) = (1-\forall_{ar})\ 1.23 \times 10^{-16}\ (1.0 + 0.17\ C^2)\ (T_{DB} + 273.)^6 \qquad (6)$$

where

$\forall_{ar}$ = reflectivity of the water surface for atmospheric radiation, ~ 0.03

C = cloud cover, decimal fraction

T_{DB} = dry bulb temperature, ^oC

Evaporative Heat Flux

$$H_{evap} = \Delta\ 8\ E_v\ W\ (e_o - e_a) \qquad (7)$$

where

Δ = water density, kg/meter^3

8 = latent heat of vaporization , kcal/kg

E_v = empirical constant, mb^{-1}

W = wind speed, meters/second

e_o = saturation vapor pressure at the temperature of the water surface, mb

e_a = vapor pressure of the air near the water surface, mb

Conductive Heat Flux

$$H_{cond} = R_B \left[\frac{T - T_a}{e_0 - e_a} \right] \frac{p_a}{1013.3} \qquad (8)$$

where

R_B = an empirical constant, 0.66

p_a = atmospheric pressure, mb

Black Body (Water Surface) Radiation

$$H_{back} = 0.97\ \Phi\ (T + 273.)^4 \tag{9}$$

where

Φ = Stefan-Boltzman constant, 1.357×10^{-11} cal/meter^2/second/^{o}K

Advected Sources of Thermal Energy

The second method by which thermal energy is transferred to the system is through advection. This primarily relates to the discharge of waters at temperatures different from the ambient waters being simulated. These would include tributaries not simulated in the model domain that flow in, as well as point and nonpoint source discharges at temperatures different from the ambient river conditions.

The parameters utilized within the model for determination of the advected thermal energy are water temperature and flow. The heat source is then calculated as the relative difference in thermal energy between the ambient water temperature and the inflowing water temperature. These values are directly input to the model segments prescribed and are an external source (S_{adv}) in Equations 1 and 2.

2.2 STATE ESTIMATION METHODS

Mathematical models used to simulate water quality in lakes, rivers, and reservoirs have traditionally been deterministic. That is, state estimates from the model are treated as being exactly determined by preceding events in time or adjacent events in space rather than as random variables. The deterministic state estimates from process models can very seldom be reconciled precisely with state estimates obtained with standard measurement devices such as thermistors and DO probes.

Model developers have attempted to resolve this problem by invoking a process most often described in terms of two steps. The first step is labeled “calibration” and the second step either “verification” or “validation.” In the calibration step, the output of the model is compared to a set of observations. If the output of the mathematical model does not agree with the measurements, the coefficients that characterize the driving forces (parameters) of the model are adjusted, or “calibrated,” until there is some form of agreement between simulated and observed results. An important assumption, rarely stated in the application of this process, is that state estimates obtained with measurement devices are without error or uncertainty. While some effort has been made to formalize the calibration process (e.g., Thomann, 1982; van der Heijde, 1990), there is no consistent approach for determining when the calibration process is complete, nor quantifying the uncertainty of either the parameters or the state estimates.

The water quality simulation package QUAL2E (Brown and Barnwell, 1987) includes algorithms for estimating uncertainty using either Monte Carlo methods or propagation of uncertainty by first-order methods. The first-order methods used in QUAL2E are similar to the variance propagation methods derived for the *prediction* mode of nonlinear forms of the Kalman filter, described below. The methods used in QUAL2E do not, however, account for either systems model or measurement error. Furthermore, estimates of parameter uncertainty must be obtained in an unspecified manner, independently from the application of the simulation package. The software documentation provides a range of uncertainty estimates (Table VI-1, Brown and Barnwell, 1987) obtained from a survey of other studies, but concludes simply that “The burden of verifying and confirming input variance estimates for a particular application lies with the user.” The ground water programming package MODFLOWP (Hill, 1994) provides a formal method for solving the so-called inverse problem of estimating model parameters and their confidence intervals from the data. The parameter estimation algorithms can be applied to a broad class of problems, including surface water analysis. The model is complex and data requirements are substantial. The available literature revealed no applications of this programming package that solve the inverse problem for surface water models.

Many studies do not even attempt to quantify the adequacy of the calibration process. For example, the criteria used in the calibration process for a mathematical model of temperature and biological productivity in the Lower Snake River (Normandeau Associates, 1999) were that "the output reproduced general patterns and long term averages of observed data or knowledge."

In the second step, "validation" or "verification," output from the calibrated model is compared to observations from an independent data set. The degree to which the simulations and observations agree is subjected to some form of hypothesis testing to determine model "validity." While goodness-of-fit criteria have been proposed by some (Bartholow, 1989; van der Heijde, 1990), many studies use qualitative statements to support the conclusion that the model has been validated. The study of the Lower Snake River referenced above concludes the verification process by simply stating that "the calibrated model predicts correct seasonal warming, maximum temperatures, and fall cooling." In another example of the calibration/verification paradigm, the Bonneville Power Administration et al. (1994) relied on a water quality model, HEC5Q, of the Columbia River to evaluate complex system operations strategies and provide support for an environmental analysis required by the National Environmental Policy Act (NEPA). Although the report of the model studies invokes the terms "calibration" and "verification," no quantitative tests or results are provided. In the case of the water temperature simulations, the report simply states, "The model has been shown to adequately represent the thermal responses throughout the river system for summer months . . . . "

These examples typify the lack of rigor and consistency associated with the calibration/verification paradigm. While calibration/verification is still considered standard practice in surface water quality modeling, there has been some effort devoted to address the lack of rigor and inconsistencies in the traditional approaches. Matalas and Maddock (1976), for example, observed that

> "Calibration implies that for the parameters of the identified model, one has control over the degree of accuracy in a particular estimation. Verification implies that the identified calibrated model, tested under controlled conditions, mimics the physical system of interest and therefore the identified calibrated verified model is to be accepted.
>
> *The words identification, calibration and verification are misleading because of their connotation of greater understanding of and control over the physical processes than actually exists."* (emphasis added)

Bartholow (1989) has an excellent discussion of these issues with regard to temperature models for surface water. Oreskes et al. (1994) noted the philosophical problems associated with attempting to verify or validate deterministic earth science models.

The techniques of state estimation avoid many of the philosophical difficulties associated with traditional modeling approaches by assuming the state estimates are random variables and that there is error associated with both the systems model and the measurement model. The methods of state estimation formulate the problem in terms of a process or systems model (Equation 1 or 2) and a measurement model (Equation 3).

The systems model (Equations 1 and 2) includes both deterministic and probabilistic components. The deterministic component of the systems model is based on the known laws of physics, chemistry, and biology. In this case, the systems model is based on scientific and empirical knowledge of the thermal energy budget. The probabilistic component represents the uncertainty in the systems model. Depending on the nature of the problem, the uncertainty can be due to level of spatial or temporal aggregation, model structure, parameter estimation and input variability. The detail with which previous studies have treated systems uncertainty in water quality or quantity studies ranges from the very basic (Moore et al., 1976) to the very complex (Rajaram and Georgakakos, 1987).

The measurement model (Equation 3) reflects the fact that estimating the state of a system with some form of measuring device cannot be done without some uncertainty. This uncertainty arises from inherent error in the measurement device, sampling error and mapping of point observations to block observations. The matrix, H_k, describes which state variables or combinations of state variables are being sampled at time, k, and can also include instrument calibration factors or transformations.

State estimation methods combine the estimates from the systems model (Equation 1 or 2) and the measurement model (Equation 3), when measurements are available, to obtain an optimal estimate of the system state. As described by Gelb et al. (1974), there are three types of state estimation problems based on the time of the estimate compared to that of the last measurement of the system state. When the state estimate precedes the last measurement, it is a *smoothing* problem; when it coincides with the last measurement it is *filtering*; and when it occurs after the last measurement it is *prediction.* The Kalman filter (Gelb et al., 1974; Schweppe, 1973) gives an unbiased, minimum squared error estimate of the system state for the filtering and prediction problems when all parameters in Equation 1 or 2 and Equation 3 are known. For the filtering problem, the Kalman filter combines the state estimates from the systems model and the measurement model. The two estimates are combined using a weighting factor determined by the relative uncertainty of the systems model compared to the uncertainty of the observation model. The weighting factor, the Kalman gain matrix, K_k, is derived by constraining the error in the estimate to be unbiased and to have a minimum mean square error.

For linear systems, the complete Kalman filter algorithm is

Systems Model: $\underline{T}_k = f_{k-1}\,\underline{T}_{k-1} + \underline{w}_{k-1} \qquad \underline{w}_k \sim N(\underline{0}, \Sigma_Q)$ (10)

Measurement Model: $\underline{T}_k = H_k\,\underline{T}_k + \underline{v}_{k-1} \qquad \underline{V}_k \sim N(\underline{0}, \Sigma_R)$ (11)

System Extrapolation: $\underline{T}_k(-) = f_{k-1}\,\underline{T}_{k-1}(+)$ (12)

Error Covariance Extrapolation: $P_k(-) = f_{k-1}\,P_{k-1}(+) f_{k-1} + \Sigma_Q$ (13)

State Estimate Update: $\underline{T}_k(+) = \underline{T}_k(-) + K_k[\underline{z}_k - H_k\,\underline{T}_k(-)]$ (14)

Error Covariance Update: $P_k(+) = [I - K_k H_k]\,P_k(-)$ (15)

Kalman Gain Matrix: $K_k = P_k(-)H_k^T[H_k\,P_k(-)H_k^T + \Sigma_R]^{-1}$ (16)

Innovations Sequence: $\nu_k = z_k - H_k T_k(-)$ (17)

where (-) denotes values at time, k, prior to filtering; (+) denotes values at time, k, after filtering; and f_k is the systems matrix.

The filter equations (Equations 10 to 17) are used for the prediction problem as well. However, in the prediction problem, the Kalman gain matrix, K_k, is zero because there are no observations available. In this case, only the systems model provides an estimate of the state. However, an additional feature of the Kalman filter is that it provides an estimate of the error covariance (Equation 13) for both the filter and the prediction problems.

The innovations sequence (Equation 17) provides a quantitative measure for parameter estimation. The innovations sequence is simply the difference between the system extrapolation (Equation 12) and the actual measurement, z_k. If one is thinking in terms of the traditional approach to model development, the innovations sequence is superficially similar to comparing the simulated state estimates with the measured state estimates. Formally, it is different in that the system extrapolation is a function of the previous measurements; the innovations sequence incorporates aspects of both the systems error and the measurement error. When the filter is optimal, the innovations sequence is unbiased and uncorrelated in time. That is,

$$E\{\nu_k\} = 0$$

and

$$E\{\nu_i \nu_j^T\} = 0, \text{ for } i>j$$

where E is the expectation operator. When the innovations sequence satisfies these criteria, it means all the deterministic information has been extracted from the systems model. When the model parameters are unknown, the innovations sequence can be used as way of finding a parameter set that provides optimal estimates. That is, the model parameters can be adjusted until the criteria given above are satisfied.

Although state estimation techniques provide the basis for dealing with issues of model and measurement uncertainty in a more rational and consistent manner than do the traditional deterministic modeling methods, there have been relatively few applications of state estimation techniques in the field of surface water modeling. Lettenmaier (1975), Moore (1973), Moore et al. (1976), and Dandy and Moore (1979) used state estimation methods to evaluate strategies for designing surface water quality monitoring systems. Lettenmaier and Burges (1976) provided a tutorial on state estimation for application to measurement system design, model building and assessment, and data extension. Koivo and Phillips (1976) used state estimation techniques to show how one could obtain optimal estimates of DO, BOD, and stream parameters for a dynamic water quality model. Beck and Young (1976) studied the use of the Extended Kalman Filter (EKF) for purposes of system identification of DO-BOD model structure. Bowles and Grenney (1978) incorporated sequential EKF's into a surface water quality model to estimate nonpoint source loadings over a 36.4-mile stretch of the Jordan River in Utah.

These examples represent some of the efforts researchers made to apply or to demonstrate how to apply state estimate methods to surface water quality modeling. Their limited success in encouraging wider use of the methods could be due to a number of factors. The methods appear somewhat complex, even though the most common technique, the Kalman filter, is a close relative of linear regression using the method of least squares. The structures of models for many surface water state variables, particularly the biological constituents, cannot always be well defined; in such cases the use of state estimation techniques may not be entirely satisfactory (Beck and Young, 1976). Solving the inverse problem for surface water quality model problems can also be technically difficult. The inverse problem can carry data-gathering burdens that are not compatible with the time and capital resources available to natural resource and regulatory agencies. Water temperature, given the state of the art, is one state variable for which the techniques of state estimation are well suited. It is simple and comparatively inexpensive to gather water temperature data. In addition, there is general agreement among researchers regarding the structure of the thermal energy budget model. Algorithms for estimating rates of energy transfer for the various components of the energy budget have also been well developed. Therefore, state estimation methods were developed to make estimates of the system state and its uncertainty for water temperature in the Columbia and Snake river main stems.

To obtain an estimate of the water temperature from the systems model, it is first necessary to decide whether to implement the solution method with a Lagrangian point of view or with an Eulerian point of view. Given the spatial and temporal complexity of the natural environment, most mathematical models using the thermal energy budget method are developed in the Eulerian frame of reference. The Eulerian frame of reference is a more intuitive way of viewing changes in concentrations simply because most measuring devices are fixed at a specific location rather than moving with the water. It is also less difficult to incorporate spatial complexity into the Eulerian framework, and, therefore, easier to add more spatial dimensions as well as more complex spatial processes such as dispersion and turbulent diffusion.

Most systems models using the Eulerian framework solve Equation 1 with either finite difference (Brown and Barnwell, 1987; Cole and Buchak, 1995; Sinokrot and Stefan, 1993; Smith, 1978) or finite element methods (Baca and Arnett, 1976). These models have generally proved valuable for simulating water temperatures in a variety of aquatic environments. However, it is well known that solutions to equations of the type characterized by Equation (1), using finite difference or finite element techniques, are subject to stability and accuracy problems (e.g., O'Neill, 1981). For water quality models, stability problems are generally not as serious as accuracy problems. When a solution becomes unstable, it is usually obvious and can generally be eliminated by reducing the time step. Accuracy problems are more pervasive and often subtle. Of particular concern to developers of finite difference and finite element methods are problems, commonly characterized as numerical dispersion, associated with the propagation of phenomena with short wavelengths. Numerical dispersion is most evident in the propagation of sharp spatial gradients when advection dominates the system. The resulting simulations can have spurious damping of high frequencies or oscillations. They are caused by differences between the rate at which the numerical scheme propagates the solution in space and the rate at which the solution would be propagated in space by the natural system.

Solution techniques based on the Lagrangian point of view (Jobson, 1981) avoid the accuracy problems associated with Eulerian methods but lack the computational convenience of a fixed grid. However, efficient accurate solution methods have been proposed which combine some of the virtues of each point of view (Cheng et al., 1984; Yeh, 1990; Zhang et al., 1993). In these hybrid Eulerian-Lagrangian methods, advective processes are treated with a Lagrangian formulation. Diffusion or dispersion processes, if present, are treated with an Eulerian formulation. With many of the hybrid methods, the need to satisfy the Courant criterion

$$U \, \Delta t/\Delta x \quad < \quad 1$$

can be relaxed. In addition, the application of state estimation techniques, as discussed below, is greatly simplified. Hybrid methods do not always eliminate numerical dispersion. However, Yeh (1990) found that the use of hybrid methods with single-step reverse particle tracking (SRPT) was definitely superior to the Eulerian method using upwind method. Zhang et al. (1993) found that hybrid methods using SRPT introduced some numerical dispersion, but that a modified form of SRPT eliminated the numerical dispersion. Cheng et al. (1984) reported that when linear interpolation was used with hybrid solution techniques, numerical dispersion was similar to that of upwind methods. Cheng et al. (1984) were able to eliminate numerical dispersion from the hybrid method by using second-order Lagrangian polynomial interpolation.

The mixed Eulerian-Lagrangian method using reverse particle tracking was chosen as the solution technique for simulating water temperature in the Columbia River system for the following reasons:

- It reduces the state-estimation (filtering and prediction) problem to one of a single state variable rather than one requiring a state variable for each finite difference or finite element grid point.
- It is relatively easy to avoid instabilities in the solution when the Courant stability criterion is exceeded.
- It provides the flexibility to expand the scope of model to include diffusion-like processes and/or more spatial dimensions.
- Although the method does not completely eliminate numerical dispersion, the results of studies described previously show that the method's ability to propagate high frequencies is generally superior to Eulerian methods. Tests of three numerical schemes showed that reverse particle tracking propagated high frequencies more accurately than both WQRRS and QUAL2E (Appendix B). These schemes are (1) reverse particle tracking, the numerical method used in this report; (2) the numerical method used by WQRRS, a water quality model commonly used by the U.S. Army Corps of Engineers (Smith, 1978; Normandeau Associates, 1999); and (3) QUAL2E (Brown and Barnwell, 1987).

The mixed Eulerian-Lagrangian method uses the concept of reverse particle tracking to implement the Lagrangian step. The river system is divided into N segments, not necessarily of the same spatial dimensions. Within each segment, however, the geometric properties of the river system are assumed to be constant during a given time step. Water temperature values are recorded only on the boundaries between segments. As an example of the method, consider Segment J (Figure 2-1). At the end of a computational time step, $t = t_{k+1}$ a particle at the downstream end of the Segment J is flagged. The flagged particle is tracked backward in time upstream until its position at the beginning of the time step, $t = t_k$, is located. The location of a particle tracked in this manner will, in general, not be precisely on a segment boundary, where water temperatures are stored by the computational scheme. Therefore, it is necessary to determine the water temperature of the particle at the beginning of the time by interpolating between the points where water temperatures are recorded. In the solution technique used in this study, this is accomplished with a second-order polynomial using Lagrangian interpolation (Press et al., 1986). Once the location of the particle and its initial water temperature are determined for the beginning of the time step, the particle is followed back downstream to its location at the end of the time step (the downstream end of Segment J). The change in water temperature for the particle during this time step is estimated using Equation 2.

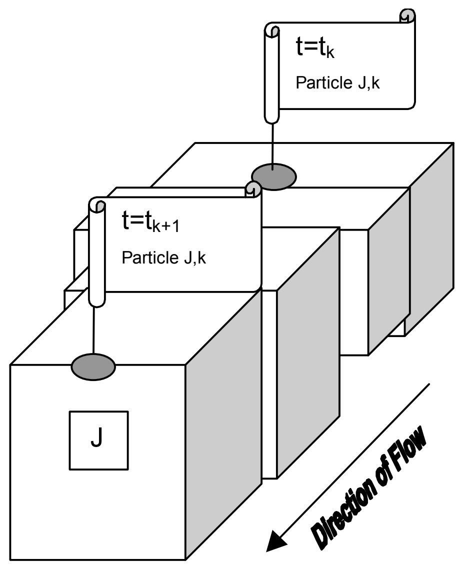

Figure 2-1. Schematic for reverse particle tracking method.

The information required for obtaining a solution to Equation 2 using reverse particle tracking includes

- River width as a function of longitudinal distance during the time step.
- Cross-sectional area as a function of longitudinal distance during the time step.
- River velocity as a function of longitudinal distance during the time step.
- Net heat exchange as a function of longitudinal distance during the time step.

The hydraulic characteristics of the unimpounded reaches of the river system are estimated from power equations relating mean velocity, area, and width (Leopold and Maddock, 1953). That is,

$$U = A_u Q^{Bu} \tag{18}$$

$$A_x = A_a Q^{Ba} \tag{19}$$

$$W_x = A_w Q^{Bw} \tag{20}$$

where

U = the river velocity, feet/second

A_x = the cross-sectional area, feet^2

Q = the river flow, cfs

W_x = the river width, feet

The coefficients, A_u, B_u, A_a, B_a, B_u, A_w, and B_w, are estimated by simulating river hydraulics conditions under various flow conditions using the methods of steady gradually varied flow (USACE-HEC, 1995). The gradually varied flow method gives estimates of the average longitudinal velocity, U, the average water depth, D, and the river width, W_x, as a function of river flow. The coefficients are determined by fitting Equations (18)-(20) to the resulting estimates using the method of least squares.

For the impounded reaches, the water surface elevation is assumed to remain constant, such that the depth and width remain constant at any cross-section and the velocity, U, is simply

$$U = Q/(W_x{*}D) \qquad (21)$$

Exchange of thermal energy across the air-water interface is estimated from Equation (4) using formulations for components of the heat budget as described by Water Resources Engineers (1968).

2.3 COMPONENTS AND STRUCTURE OF MODEL SYSTEM

Based on the theoretical formulations discussed in Section 2.2, a heat budget model has been developed that projects the temperature conditions for a water body within a one-dimensional framework. The model projects the temperature under a specified set of heat flux conditions from atmospheric sources, upstream boundaries, and adjacent tributary inflows. The model projects the temperature and provides evaluation and adjustment to the model uncertainty using the Kalman filter described previously. A detailed description of the model application to the Columbia River is presented in Chapter 3.

Figure 2-2 presents a general flow chart of the model system developed. Inputs include the system geometry, the heat flux across the air-water interface, the tributary inflows, and the model hydraulic parameters.

As this is a heat budget model, the hydraulic parameters must be determined a priori to the simulation. This is done through application of another model or methodology that provides the coefficients for input to the model. These then become model input conditions rather than parts of the overall simulation. The specifics of the hydraulic parameters are presented in detail for the Columbia River application in Section 3.5.

The tributary inflows and the heat flux across the air-water interface are the other input parameters for the model. These are prescribed as time series for the period of simulation. The tributary information required is the flow rate and temperature as a function of time. The heat budget information required is the input to the six terms listed in Equation 4.

Using these inputs, the model solves the system model equation for each model segment using the mixed Eulerian-Lagrangian approach and redefines the interim system state based upon the inputs over the prescribed time period.

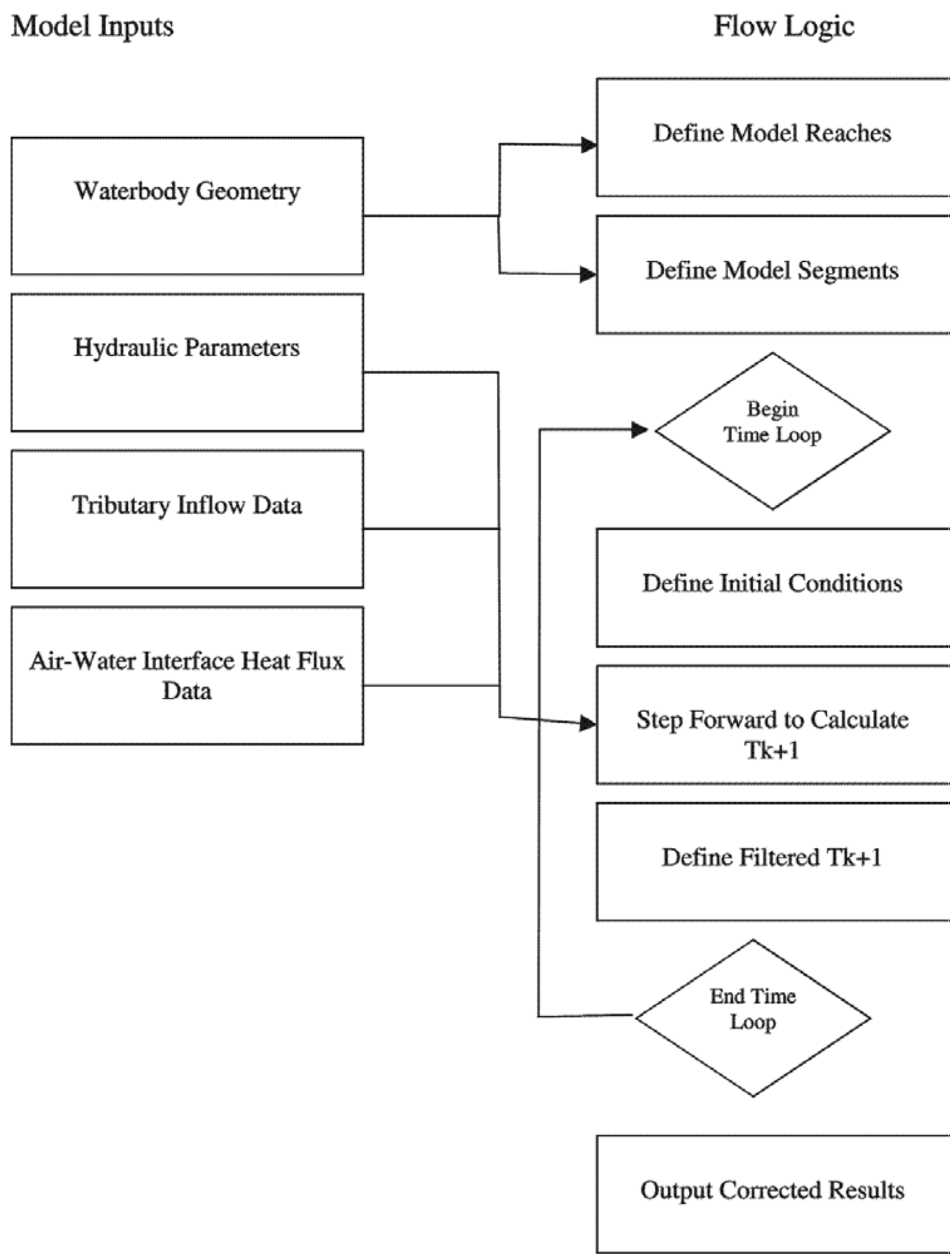

Figure 2-2. General Model Structure.

CHAPTER 3: APPLICATION OF TEMPERATURE MODEL TO COLUMBIA RIVER SYSTEM

3.1 SYSTEM HYDROLOGY BOUNDARIES AND ASSUMPTIONS

The boundaries of the Columbia River system for the assessment of water temperature include the Columbia River from the International Boundary (River Mile 745.0) to Bonneville Dam (River Mile 145.5) and the Snake River near Anatone, Washington (River Mile 168.9) to its confluence with the Columbia River near Pasco, Washington. With the exception of Grand Coulee Dam and its impounded waters, Lake Franklin D. Roosevelt (FDR), all the hydroelectric projects on these segments of the Columbia and Snake rivers have limited storage capacity and are operated as run-of-the-river reservoirs. Because of its large storage capacity (Table 1-3), Lake FDR is used for flood control as well as providing water for irrigation and generation of hydroelectric power. Typical reservoir elevations for Lake FDR show substantial annual variation (Figure 3-1).

Table 3-1. Sources of advected thermal energy in the Columbia River below Grand Coulee Dam and the Snake River below its confluence with the Grande Ronde River

Source	Location
Clearwater River	Snake R.M. 140.0
Potlatch Corporation	Snake R.M. 139.8
Tucannon River	Snake R.M. 62.2
Palouse River	Snake R.M 59.5
Lower Snake River Groundwater	Snake R.M. 168.0 – R.M. 0.0
Okanogan River	Columbia R.M. 533.5
Methow River	Columbia R.M. 523.9
Chelan River	Columbia R.M. 503.3
Crab Creek	Columbia R.M.410.8
Yakima River	Columbia R.M.335.2
Walla Walla River	Columbia R.M. 314.6
John Day River	Columbia R.M. 218.0
Deschutes River	Columbia R.M. 204.1
Upper Columbia River Groundwater	Columbia R.M. 596.0 – R.M. 292.0
Lower Columbia River Groundwater	Columbia R.M. 292.0 – R.M. 146.1

Run-of-the-river reservoirs are those for which reservoir elevation is kept more or less constant; water coming into the reservoir is passed directly through the reservoir. Typical run-of-the-river reservoirs are Lower Granite Reservoir and John Day Reservoir, the two largest run-of-the-river reservoirs on the Snake and Columbia rivers. Surface elevations for these two reservoirs during 1998 are shown in Figures 3-2 and 3-3, respectively.

The differences between the run-of-the-river reservoirs and Lake FDR, with respect to both their modes of operation and storage capacity, give rise to differences in their respective thermal regimes. For the run-of-the-river reservoirs, the spatial variability of temperature within a cross section perpendicular to the direction of flow is generally less than 1 ^{o}C (McKenzie and Laenen, 1998) except near the forebay of some dams. In Lake FDR, vertical variations in water temperature of up to 5 ^{o}C have been observed at various locations along the longitudinal axis of the reservoir. Because of this difference in the thermal regimes, the run-of-the-river projects

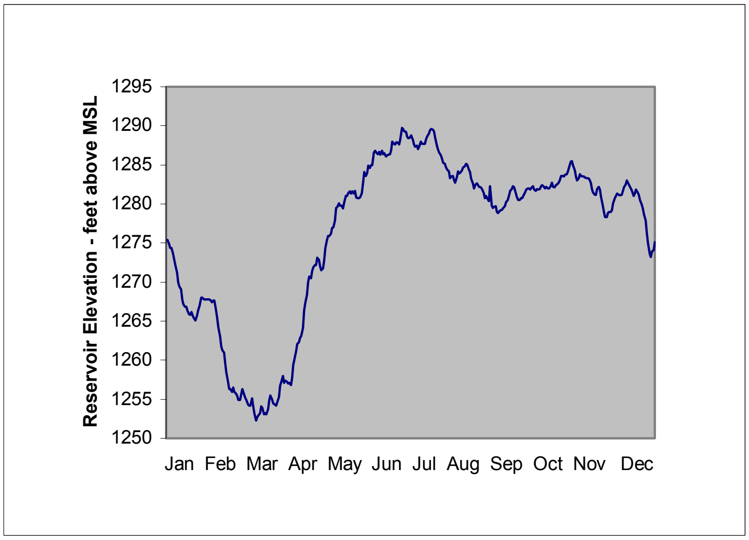

Figure 3-1. Surface elevations in Lake Franklin D. Roosevelt during 1998.

can be modeled as systems with variability in the longitudinal direction only. Lake FDR, however, is treated as a system with both vertical and longitudinal spatial variability using the water quality modeling system CEQUAL-W2 (Cole and Buchak, 1995). The assessment of water temperature in Lake FDR will be described in a later study.

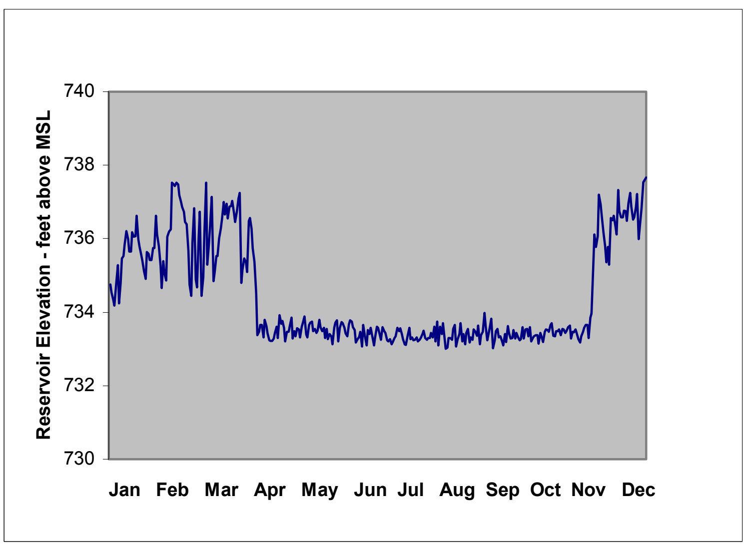

Figure 3-2. Surface elevations in Lower Granite reservoir during 1998.

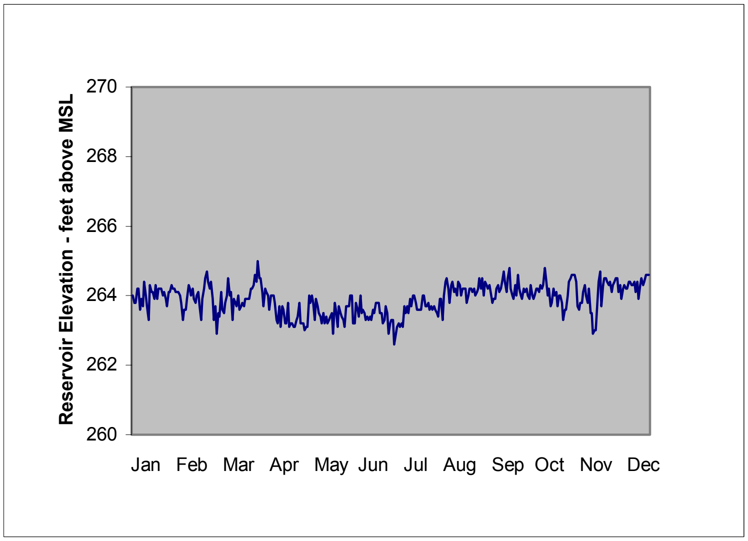

Figure 3-3. Surface elevations in John Day reservoir during 1998.

This report describes the development and application of a one-dimensional thermal energy model for the run-of-the-river reservoirs. The system boundaries for the model of the run-of-the-river segments are the main stems of the Columbia River from the tailwaters of Grand Coulee Dam (Columbia River Mile 596.6) to Bonneville Dam (Columbia River Mile 145.5) and the Snake River from its confluence with the Grande Ronde River (Snake River Mile 168.7) to its confluence with the Columbia River near Pasco, Washington (Snake River Mile 0.0). Advected thermal energy from ground water, point sources, and major tributaries (Table 3-1) to these segments are treated as inputs to the main stem rivers in this analysis.

3.2 TIME AND LENGTH SCALES

To accomplish the management objectives of the analysis, it is necessary to simulate daily average water temperatures as a function of longitudinal distance in the Columbia and Snake rivers. This establishes an approximate lower limit on system time scales and on data requirements. Stability and accuracy issues associated with solutions to Equation 2 can impose a requirement of even smaller time increments to obtain reliable solutions. However, the simulated results for time scales less than a day are valuable only in terms of their contribution to the solution accuracy. Because the time scale of the input data is equal to or greater than one day, there is no physical significance to higher-frequency output associated with the need to obtain a stable solution.

In an effort to include the environmental variability due to hydrology and meteorology, the largest time scales are on the order of two decades. The time scales are constrained by the hydrologic data available for the Columbia River system under existing management. Existing management in this case means operation of the system after the construction of the last hydroelectric project, Lower Granite Dam and Reservoir, completed in 1975. The simulation time scale, therefore, is 1975 to 1995.

The length scales for the analysis are determined by a number of factors. These factors include the availability of geometric data, spatial variability in the river geometry, and computational stability and accuracy. Data availability often provides the most severe constraint; however, there are ample data for describing river geometry in both the Columbia and Snake rivers within the boundaries of this analysis. The primary factor determining the length scale of this analysis is the need to achieve stable, accurate solutions. Length scales are such that the time it takes a parcel of water to traverse a given computational segment is always equal to or less than 1 day. For the Columbia and Snake rivers, this results in length scales on the order of 1 to 10 miles.

3.3 RATIONALE FOR APPROACH

Idealizing the largest part of the Snake and Columbia River system in terms of a one-dimensional model is based on the assumption that the primary processes affecting the thermal energy budget are advection and the transfer of thermal energy across the air-water interface. This assumption is in keeping with the management objective of providing a primary temperature assessment for the water quality planning process as required by Section 303(d) of the Clean Water Act. Based on previous work in the Columbia and Snake rivers (Raphael, 1962; Yearsley, 1969; Jaske and Synoground, 1970), a model of this type should capture the major features of water temperature impacts in this system. As described above, a number of other temperature assessments of the Columbia and Snake rivers (Bonneville Power Administration et al., 1994; Normandeau Associates, 1999) are based on one-dimensional models of the thermal energy budget. The mixed Lagrangian-Eulerian scheme for handling advection was chosen based on studies such as those done by Yeh (1990) and Zhang et al. (1993).

3.4 MODEL INPUT DATA

Water Temperature

The extensive water temperature data records for the Columbia and Snake rivers have been assembled and reviewed for quality by McKenzie and Laenen (1998). In addition, McKenzie and Laenen (1998) organized the data in electronic formats for rapid analysis. The results of their work provide a water temperature data set for the Columbia and Snake rivers, which can be used to describe uncertainty in the temperature model. The data quality analysis performed by McKenzie and Laenen (1998) provides a basis for characterizing the uncertainty associated with the measurements.

McKenzie and Laenen (1998) compiled data for the main stem Columbia and Snake rivers. Temperature data for the tributaries included in the analysis were obtained from observations made by the Idaho Power Company, Washington State Department of Ecology (DOE) and the U.S. Geological Survey (USGS). The location of monitoring locations, period of record, and frequency of analysis are shown in Table 3-2.

River Geometry

River geometry is needed to characterize the hydraulic properties of the river as a function of flow and time. The basic information required is elevation of the river channel above mean sea level at a sufficient number of cross sections so as to adequately describe water depth, water width, and velocity as a function of river flow. A number of sources, described in Table 3-3, were used to obtain the data needed.

Hydrology

River hydrology data for the main stem Columbia and Snake rivers, as well as the major tributaries, were obtained from the records maintained by the U.S. Geological Survey. Gaging stations used in the study are shown in Table 3-4. Estimates of groundwater return flow were obtained from Hansen et al. (1994).

Table 3-2. Locations of water temperature monitoring sites for major tributaries of the Columbia and Snake Rivers in the study area

Station Name	Agency	Station Number	Station Location		Period of Record
			Latitude	Longitude	
Clearwater River at Spalding	U.S. Geological Survey	13342500	46°26'55"	116°49'35"	1911-1996
Tucannon River at Powers	Washington DOE	35B060	46°32'18"	118°09'18"	10/17/73 – 09/02/96
Palouse River at Hooper	Washington DOE	34A070	46°45'33"	118°08'49"	07/30/59 – 09/02/96
Okanogan River at Malott	Washington DOE	49A070	48°16'53"	119°42'12"	11/17/66 – 09/10/96
Methow River at Pateros	Washington DOE	48A070	48°04'29"	119°57'20"	07/29/59 – 09/10/96
Chelan River at Chelan	Washington DOE	47A070	47°50'23"	120°01'11"	07/20/60 – 09/14/94
Crab Creek near Beverly	Washington DOE	41A070	47°11'23"	119°15'54"	10/24/61 – 09/05/94
Yakima River at Kiona	Washington DOE	37A090	46°15'13"	119°28'37"	03/20/68 – 09/09/96
John Day River at Highway 206	Oregon DEQ	404065	45°28'37"	120°28'07"	02/11/73 – 12/04/97
Deschutes River at Deschutes Park	Oregon DEQ	402081	45°37'40"	120°54'13"	07/16/62 – 12/01/97

Table 3-3. Sources of data for developing the hydraulic characteristics of the Columbia and Snake rivers

River Segment	Data Source
Columbia River: Grand Coulee Dam to Confluence with the Snake River	Columbia River Thermal Effects cross-sectional data (Yearsley, 1969)
Snake River: Lewiston, Idaho to Confluence with the Columbia River	U.S. Army Corps of Engineers (Walla Walla District) HEC-6 cross-sectional data
Columbia River: Confluence with the Snake River to Bonneville Dam	NOAA Navigation Charts

Table 3-4. U.S. Geological Survey gaging stations for the main stem Columbia and Snake Rivers and their major tributaries in the study area

Station Name	Station Number	Station Location		Period of Record	Drainage Area (mi^2)	Average Annual Flow (cfs)	Gage Datum (feet above MSL)
		Latitude	Longitude				

Station Name	Station Number	Station Location		Period of Record	Drainage Area (mi^2)	Average Annual Flow (cfs)	Gage Datum (feet above MSL)
		Latitude	Longitude				
Snake River at Anatone, WA	13334300	46°05'50"	116°58'36"	1958-1995	92960	35100	807.
Clearwater River at Spalding, ID	13342500	46°26'55"	116°49'35"	1911-1996	9570	15200	4360.
Tucannon River near Starbuck, WA	13344500	46°39'20"	118°03'55"	1915-1992	431	175	730.
Palouse River at Hooper, WA	13351000	46°45'31"	118°05'52"	1898-1994	2500	580	1041.
Columbia River at Grand Coulee, WA	12436500	47°57'56"	118°58'54"	1923-1995	74700	107200	900.
Okanogan River at Malott, WA	12447200	48°37'57"	119°42'12"	1966-1994	8080	3000	784.
Methow River at Pateros, WA	12449950	48°04'39"	119°59'02"	1959-1994	1772	1550	900.
Chelan River at Chelan, WA	12452500	47°50'05"	120°00'43"	1904-1993	924	2090	-----
Crab Creek near Beverly, WA	12472600	46°49'48"	119°49'48"	1951-1994	4840	200	500.
Yakima River at Kiona, WA	12510500	46°15'13"	119°28'37"	1906-1994	5615	3600	454.
Walla Walla River at Touchet, WA	14018500	46°01'40"	118°43'43"	1951-1996	1657	570	405.
John Day River at McDonald Ferry, OR	14048000	45°35'16"	120°24'30"	1905-1994	7580	2080	392.
Deschutes River at Moody, OR	14103000	45°37'20"	120°54'05"	1898-1994	10500	5800	168.

Meteorology

Meteorological data, including solar radiation, barometric pressure, cloud cover, wind speed, air temperature (dry-bulb), and relative humidity, are required for the thermal energy budget calculations. First order weather stations in the Columbia Basin maintained by the Weather Service and for which data are archived in the National

Climatological Data Center (NCDC) include Lewiston, Idaho; Spokane, Washington; and Yakima, Washington. Data are available for these locations at 3-hour intervals from the NCDC SAMSON data sets. The period of record for each of these stations is shown in Table 3-5.

Table 3-5. First-order meteorological stations used to estimate heat budget parameters for the Columbia and Snake rivers

Station Name	WBAN #	Period of Record	Latitude	Longitude	Station Elev (feet above MSL)
Lewiston, Idaho	24149	01/01/1948-12/31/1997	46^{o} 23’00”	117^{o} 01’00”	1436
Pendleton, Oregon	24155	01/01/1948-12/31/1997	45^{o} 41’00”	118^{o} 51’00”	1482
Spokane, Washington	24157	01/01/1948-12/31/1997	47^{o} 38’00”	117^{o} 32’00”	2356
Yakima, Washington	24243	01/01/1948-12/31/1997	46^{o} 34’00”	120^{o} 23’00”	1064

Stations with maximum and minimum daily air temperatures are more numerous and are included in the NCDC Local Climatological Data Sets. The selected stations in the Columbia Basin selected are shown in Table 3-6.

Table 3-6. Weather stations from the Local Climatological Data Sets included in the parameter estimation process for heat budget calculations

Station Name	Station #	Latitude	Longitude	Station Elevation	Period of Record
Connell	1690	46^{o} 45’37	117^{o}10’10”	1020.	11/01/1960 – 12/31/1997
Coulee Dam	1767	47^{o} 57’00	119^{o}00’00”	1700.	06/01/1948 – 12/31/1997
The Dalles	8407	45^{o} 36’00”	121^{o}12’00”	102	07/01/1948 – 12/31/1997
Pullman	6789	46^{o} 45’37”	117^{o}10’10”	2545	10/21/1940 – 12/31/1997
Richland	7015	46^{o} 23’00”	117^{o}01’00”	373	06/01/1948 – 12/31/1997
Wenatchee	9074	47^{o} 25’00”	120^{o}19’00”	640	02/08/1877 – 12/31/1997

The U.S. Bureau of Reclamation maintains a network of agricultural weather stations called AgriMet stations. These stations report daily averages for all of the necessary meteorological data except cloud cover. They also report daily average solar radiation. Selected stations from the AgriMet network are shown in Table 3-7.

Table 3-7. Selected AGRIMET weather stations in the Columbia Basin maintained by the U.S. Bureau of Reclamation

Station ID	Station Name	State	Elevation	Latitude	Longitude	Install Data
GERW	George	WA	1150	47^{o} 02’ 38”	119^{o} 38’ 32”	5/14/86
GOLW	Goldendale	WA	1680	45^{o} 48’ 43”	120^{o} 49’ 28”	11/27/91
HERO	Hermiston	OR	600	45^{o} 47’ 56”	119^{o} 31’ 46”	5/17/83
LEGW	Legrow	WA	580	46^{o} 12’ 19”	118^{o} 56’ 10”	7/17/86
ODSW	Odessa	WA	1650	47^{o} 18’ 32”	118^{o} 52’ 43”	4/24/84

An analysis of a 24-year record (January 1, 1972, to December 31, 1995) for the four NCDC SAMSON weather stations showed a high degree of correlation between stations for dry bulb and dew point temperature (Table 3-8). Average annual air temperatures showed more variability among the stations than did dew point. Cloud cover was correlated, though not to the same degree as dry bulb and dew point temperature. Mean annual cloud cover in Yakima differed substantially from that of the other three SAMSON stations in the Columbia Basin. As expected, wind speed showed a much lower correlation among stations as well as more variability in the mean annual value.

Table 3-8a. Correlation coefficients and annual average for average daily air temperature collected at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.977	0.985	0.969
Pendleton		1.000	0.976	0.966
Spokane			1.000	0.975
Yakima				1.000
Annual Average	11.6 ^oC	11.2 ^oC	8.6 ^oC	10.1 ^oC

Table 3-8b. Correlation coefficients and annual average for average daily dew point at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.932	0.937	0.894
Pendleton		1.000	0.916	0.899
Spokane			1.000	0.919
Yakima				1.000
Annual Average	2.4 ^oC	2.0 ^oC	1.0 ^oC	1.5 ^oC

Table 3-8c. Correlation coefficients and annual average for average daily sky cover at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.851	0.837	0.712
Pendleton		1.000	0.790	0.830
Spokane			1.000	0.784
Yakima				1.000
Annual Average	64.1%	59.0%	61.5%	54.9%

Table 3-8d. Correlation coefficients and annual average for average daily wind speed at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.500	0.540	0.390

Pendleton		1.000	0.560	0.0.560
Spokane			1.000	0.530
Yakima				1.000
Annual Average	2.86 m/s	3.79 m/s	3.97 m/s	3.20 m/s

3.5 PARAMETER ESTIMATION

The parameter estimation process addresses both the deterministic and probabilistic parameters in the model. The deterministic elements include the source term, f_k, and, implicitly, the travel times of parcels in the Lagrangian reference system. The components of the heat budget (Equation 4) and the advected thermal inputs from tributaries and groundwater compose the source terms. The parameters required to determine the travel times are derived from an analysis of the system hydraulics. It should be noted these parameters are not really deterministic; rather, they are random variables. For the purposes of this analysis, the composite error resulting from variability in the so-called deterministic parameters is included in the error term, $\underline{w}_{k-1}$, in Equation 10. Given this assumption, the probabilistic parameters are the means and variances of the error terms for the measurement model and the systems model.

In this study, the parameter estimation process is implemented in three steps. In the first step, the deterministic parameters are estimated, ideally, from first principles or, as is more often the case, from available research. Next, the estimated deterministic parameters are adjusted until the simulated results from the systems model are approximately unbiased. The systems model is unbiased if the mean of the innovation vector is small, where the innovation vector is the difference between time-updated simulations from the systems model and the actual measurements (Van Geer et al., 1991). Assuming the actual measurement bias and their variances are known, the final step in the parameter estimation process is to estimate the variance, Γ_Q, of the systems model.

Hydraulic Coefficients

As described previously, the hydraulic properties of each unimpounded river segment are estimated from relationships of the type given in Equations 18 to 20. Because a primary objective of the study is to assess the impact of impoundments, it was necessary to estimate these coefficients for two states of the system: one with dams in place and one without dams. For the case in which the dams were in place, the results from the USACE HEC-5Q model of the Columbia and Snake rivers were provided by Nancy Yun of the USACE North Pacific Division Office. They are given in Tables C-1 and C-2, Appendix C. The only unimpounded reach under the present configuration is the Hanford Reach. The coefficients in Equations 18 to 20 for the Hanford Reach are given in Table C-3, Appendix C.

For the unimpounded conditions, geometric properties of the Columbia and Snake rivers, obtained from the sources given in Table 3-3, were used as input data to HEC-RAS (USACE-HEC, 1995), the steady gradually varied flow model developed by the U.S. Army Corps of Engineer's Hydrologic Engineering Center. Surface elevations of the Columbia and Snake rivers were estimated for flows of 150,000, 250,000, and 500,000 cfs in the Columbia River and 60,000, 120,000, and 240,000 cfs in the Snake River. For each of these flows, the average water depth, surface width, and velocity at selected locations were used to estimate the coefficients in Equations 18 to 20 using the methods of least squares. The coefficients obtained in this manner are given in Table C-4 and C-5, Appendix C.

Water Balance

The daily flow at any location in either river was determined from the sum of estimated ground water return flow (Hansen et al., 1994) and the daily gaged flow of the main stem headwaters and the tributaries upstream from the location. This assumes the following:

- Information regarding flow changes is transmitted instantaneously to locations downstream.
- Tributary sources other than those shown in Table 3-1 are negligible.
- The river gradient is sufficiently high such that the slope terms dominate (Henderson, 1966).

Heat Flux Across Air-Water Interface

The variables in the meteorological input file (*.HOT) were either directly measured or calculated from daily averaged data. These variables were then used to quantify the heat flux terms used in the energy budget method. The variables in the meteorological input file were determined as follows:

- Net Solar Radiation – calculated using equation (5)
- Net Atmospheric Radiation – calculated using Equation 6
- Dry-Bulb Temperature – directly measured
- Wind Speed – directly measured
- Factor for Bowen Ratio (psychrometric constant) – calculated using the following equation:

$$R_B = (c_a P) / (0.622\ 8) \qquad (22)$$

where

c_a = heat capacity of air, cal/g/C, 0.24;

P = pressure at sea level, mb, 1013.3;

λ = latent heat of vaporization, cal/g;

$$\lambda = 597.3 - (0.564\ T_d)\text{; and} \qquad (23)$$

T_d = dry-bulb temperature, degrees Celsius

- Vapor Pressure – was calculated using the following equation

$$e_a = 6.11\ \mathrm{EXP}\ (17.27\ T_{dew}) / (237.3 + T_{dew}) \qquad (24)$$

where,

T_{dew} = dew-point temperature, degrees Celsius

Photo Period – this variable is not used in this model.

Initial Water Temperatures

Daily water temperatures are not always available for the locations used as initial conditions on the tributaries (Table 3-1) of the Columbia and Snake. For most stations, long-term sampling with a period of two to four weeks provides sufficient data to synthesize stream temperatures using air temperature. In their study of 584 USGS stream gaging stations within the contiguous United States, Mohseni et al. (1998) used a nonlinear model of the following type to synthesize water temperatures:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \qquad (25)$$

where

T_s = the weekly stream temperature

T_a = the weekly air temperature from a nearby weather station and

∀, ∃, (, and μ are determined by regressing the observed water temperature data on the air temperature data by minimizing the squared error with the downhill simplex method (Nelder and Mead, 1965).

Separate functions of the type defined in Equation 25 are used to describe the rising limbs and the falling limbs of the annual water temperature cycle in each of the tributaries. Mohseni et al. (1998) concluded that the method was accurate and reliable at 89 percent of the streams. Mohseni et al. (1998) also found that the method gave good results even when the air temperature measurements were not in proximity to the stream gaging locations.

The parameters obtained for the tributaries following the method of Mohseni et al. (1998), for both rising and falling limbs, at each of the input locations, are given in Table 3-9.

For the initial water temperatures on the main stem Columbia River, scroll case and total dissolved gas data from Chief Joseph Dam were combined to provide a long-term record. On the Snake River, the USGS data from the monitoring site at Anatone, Washington, was combined with data collected by Idaho Power Company and the Columbia River Intertribal Fish Commission to form a long-term record.

Measurement Bias and Error

The analysis of water temperature in the Columbia and Snake rivers by McKenzie and Laenen (1998) provides the basis for an initial estimate of the probabilistic parameters of the measurement model (Equation (3)). The data reviewed by McKenzie and Laenen (1998) were obtained from scroll case measurements and

Table 3-9. Parameters for estimating input temperatures of main stem and tributaries using nonlinear regression methods described by Mohseni et al. (1998)

River	Weather Station	Week for Rising Limb / Week for Falling Limb	T_{max}	β	γ	μ
Methow River	Wenatchee	1	22	14.4976	0.2007	0.5576
		30	22	12.9058	0.1787	0.4964
Walla Walla River	Yakima	1	29	12.7334	0.1763	0.4897
		30	29	11.6612	0.1615	0.4485
Clearwater River	Lewiston	1	24	16.2527	0.2250	0.6251
		30	24	13.00	0.1800	0.500

River	Weather Station	Week for Rising Limb / Week for Falling Limb	T_{max}	β	γ	μ
Chelan River	Wenatchee	1	26	13.0000	0.1800	0.500
		30	26	8.3590	0.1157	0.3215
Crab Creek	Wenatchee	1	26	11.2747	0.1561	0.4336
		30	26	11.4084	0.1580	0.4388
Deschutes River	Yakima	1	24	10.5902	0.1466	0.4073
		30	24	8.0669	0.1117	0.3103
John Day River	Lewiston	1	29	13	0.1800	0.5000
		32	29	12.3896	0.1715	0.4765
Okanogan River	Wenatchee	1	26	15.4810	0.2144	0.5954
		30	26	13.3483	0.1848	0.5134
Palouse River	Yakima	1	28	14.2740	0.1976	0.5490
		30	28	14.7654	0.2044	0.5679
Tucannon River	Lewiston	1	22	12.2640	0.1698	0.4717
		32	22	11.3405	0.1570	0.4362
Wenatchee River	Wenatchee	1	23	16.5413	0.2290	0.6362
		30	23	12.5088	0.1732	0.4811
Yakima River	Yakima	1	28	12.7321	0.1763	0.4897
		30	28	11.9158	0.165	0.4583

measurements made in conjunction with total dissolved gas monitoring. The scroll case measurement reflects the temperature of the water as it enters the generating turbine and is measured by reading the level of a mercury thermometer. The total dissolved gas monitoring program uses a temperature probe located in the forebay of each of the dams usually at a depth of 15 feet or more.

The quality, bias, and variability of these data vary considerably from site to site. For the scroll case data, McKenzie and Laenen (1998) report frequent "stepping" of the data. Stepping is characterized by periods of several days when the reported temperature is constant. Scroll case temperatures are measured by visual observations from mercury thermometers and recorded manually, usually on a daily basis. McKenzie and Laenen (1998) suggest that the measurement method might have contributed to the "stepping" and that the stepping might have been due to the frequency with which scroll case temperatures were measured and reported in the past.

The variation in data quality makes the task of quantifying measurement bias and error a difficult one. McKenzie and Laenen (1998) report bias in the measurements as high as 2.0 ^{o}C and variability as high as 2.0 ^{o}C at certain sites and during certain periods of the year. However, at most sites and for recent data (post–1990), bias is in the range of 0.0-1.5 ^{o}C and variability is generally less than 1.0 ^{o}C.

Systems Model Bias and Error

The approach to estimating the probabilistic parameters for the systems model (Equation 2) follows that of Van Geer et al. (1991). Initial estimates of deterministic parameters are obtained from some combination of first principles and existing research. These parameters include the heat transfer across the air-water interface, advected thermal energy from tributaries and point sources and hydraulic properties of the river system. Adjustments are made to certain parameters until the mean of the innovations vector (Equation 17) is small.

The parameters selected for adjustment are constrained by assuming that any error in the basic heat transfer components (Equations 5 to 9), the advected energy from tributaries, and the hydraulic computations can be aggregated into the systems model error, $\Gamma_Q(t)$. Given these constraints, what remains to be adjusted is the choice of meteorological stations used to estimate the basic heat transfer components and the evaporation rate. This formulation of the evaporation was obtained from the comprehensive energy budget of Lake Hefner in Oklahoma (Marciano and Harbeck, 1952) and has been shown to perform satisfactorily for other water bodies (Bowie et al., 1985). However, there is uncertainty in the empirical constant, E_v (Kohler, 1954; Bowie et al., 1985). There is also uncertainty and variability associated with the meteorological variables, wind speed, W, and vapor pressure, e_a. The uncertainty in the meteorological variables, as discussed below, is primarily a result of the assumption in this study that wind speed and vapor pressure can be treated as regional phenomena. The approach used in this report has been to assume the meteorological variables can be obtained from the NCDC SAMSON data sets and treat the empirical constant, E_v, as a parameter that can be estimated during the process described above.

The choice of appropriate meteorological stations for estimating the heat budget at the spatial scale of this analysis must take into account regional variations in weather under the constraint of a limited number of stations with complete data. The problem is not unique to this study. The analysis of systems operations in the Columbia Basin (Bonneville Power Administration et al., 1994) used the data from three weather stations (Boise, Idaho; Lewiston, Idaho; and Spokane, Washington) to develop the heat budget for the Columbia, Snake, and Clearwater rivers. These data were used to describe surface heat exchange from and including Brownlee Reservoir on the Snake to the confluence with the Columbia; the Clearwater River from and including Dworshak Reservoir and the Columbia River from the International Border to Bonneville Dam. A study of thermal energy in the Hells Canyon complex by Idaho Power Company (Harrison et al., 1999) used the combined meteorological data from Parma, Idaho, and Prairie City, Oregon, to predict water temperatures in Brownlee Reservoir from approximately Snake River Mile 335 to Snake River Mile 285. Parma is approximately 50 miles from Brownlee Reservoir, while Prairie City is approximately 100 miles from Brownlee Reservoir.

As shown in Table 3-8, there are strong regional correlations among certain meteorological variables in the Columbia Basin, particularly air temperature, dew point, and cloud cover. Regional correlations for wind speed are not as strong because of the influence of topography. There is some regional variation in the climate as reflected in the annual average values (Table 3-8). Data from two classes of meteorological stations are available to estimate these components, as described previously. Some Surface Airways (SAMSON) stations report the complete suite of meteorological variables. There is extensive coverage of daily maximum and minimum air temperatures from the Local Climatological Data (LCD). Data from the SAMSON stations were used to expand the spatial coverage for heat budget analysis. This was accomplished by assuming that wind speed, cloud cover, relative humidity, and barometric pressure are large-scale phenomena and that air temperature is more of a local phenomenon. Several LCD stations were augmented with SAMSON data in this way to provide more spatial coverage of the surface heat transfer. Meteorological data were assigned to river segments based on a qualitative assessment of local meteorology. A number of combinations of stations were evaluated in an effort to achieve unbiased simulations. The final configuration of stations and the values of the empirical constant, E_v, for each river segment are given in Table 3-10.

Table 3-10. Final configuration of weather stations used to estimate the heat budget terms for the mathematical model of water temperature in the Columbia and Snake Rivers.

Weather Station	Station Type	Evaporation Coefficient (mb^{-1})	River Segments
Lewiston, Idaho	SAMSON	1.45×10^{-9}	Snake River from Lewiston, Idaho to the Confluence with the Columbia
Wenatchee, Washington	LCD	1.55×10^{-9}	Columbia River from Grand Coulee Dam to Rock Island Dam
Yakima, Washington	SAMSON	1.40×10^{-9}	Columbia River from Rock

Richland, Washington	LCD	1.10×10^{-9}	Island Dam to the Confluence with the Snake Columbia River from the confluence with the Snake to Bonneville Dam

Using the parameters estimated above, estimates of the system model error variance, $\Gamma_Q(t)$, are obtained by adjusting the estimated variance until the theoretical variance for the innovations vector is approximately equal to the sample variance (Mehra, 1972). The theoretical variance is given by (Kailath, 1968)

$$E\{\nu_k \nu_k^T\} = H P_k(-) H^T + \Sigma_R \tag{26}$$

and the sample variance, S, by

$$S = \frac{1}{m}\sum_{k=1}^{m} \nu_k \nu_k^T \tag{27}$$

This is an iterative process because the innovations vector is a function of the deterministic parameters and the probabilistic parameters. In addition, there are bias and error in the observations (McKenzie and Laenen, 1998), as described previously. The systems model error estimate was obtained by first finding a set of meteorological stations, which provided good (in a qualitative sense) agreement. This was followed by an adjustment of measurement bias and error for the total dissolved gas temperature data, within the range estimated by McKenzie and Laenen (1998). The final values for systems model variance, Σ_Q, and measurement error and bias are given in Table 3-11.

After completing the parameter estimation process for both the deterministic and probabilistic parameters, the systems model was run in the predictive mode. That is, the measurements were not used to update the state estimate. Running the model in the predictive mode provides a way of comparing state estimates from the systems model with the state estimates from the measurement model in a manner similar to the traditional approaches using the calibration and verification paradigm. The output from these simulations is shown in Figures 3-4 through 3-12. Various statistics that can be used to assess model performance are given in Appendix D.

Table 3-11. Measurement bias, measurement error variance and systems dynamic error variance at locations of scroll case temperature measurements on the Columbia and Snake Rivers

Location of Measurement	Measurement Bias (°c)	Error Variance: Measurement °c²	Error Variance: Systems Dynamics °c²
Lower Granite Dam	0.0	0.50	0.008
Little Goose Dam	0.0	0.50	0.008
Lower Monumental Dam	0.0	0.50	0.008
Ice Harbor Dam	0.0	0.5	0.008
Rock Island Dam	0.5	0.50	0.008
Priest Rapids Dam	0.0	0.50	0.008
McNary Dam	1.0	0.50	0.008
The Dalles Dam	1.0	0.50	0.008
Bonneville Dam	1.5	0.50	0.008

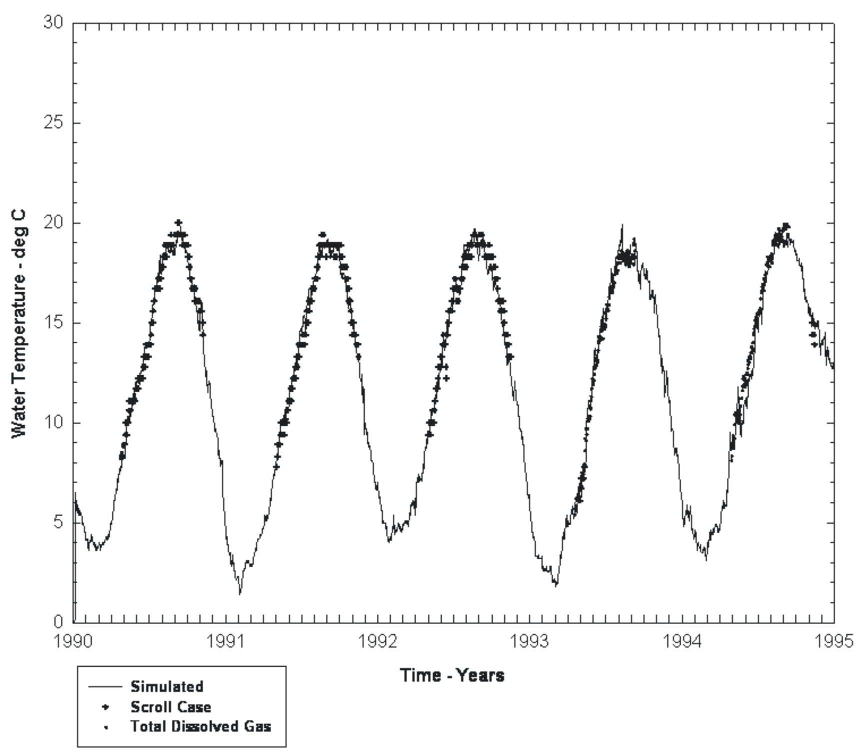

Figure 3-4. Simulated and observed water temperatures at Wells Dam for the period 1990–1994.

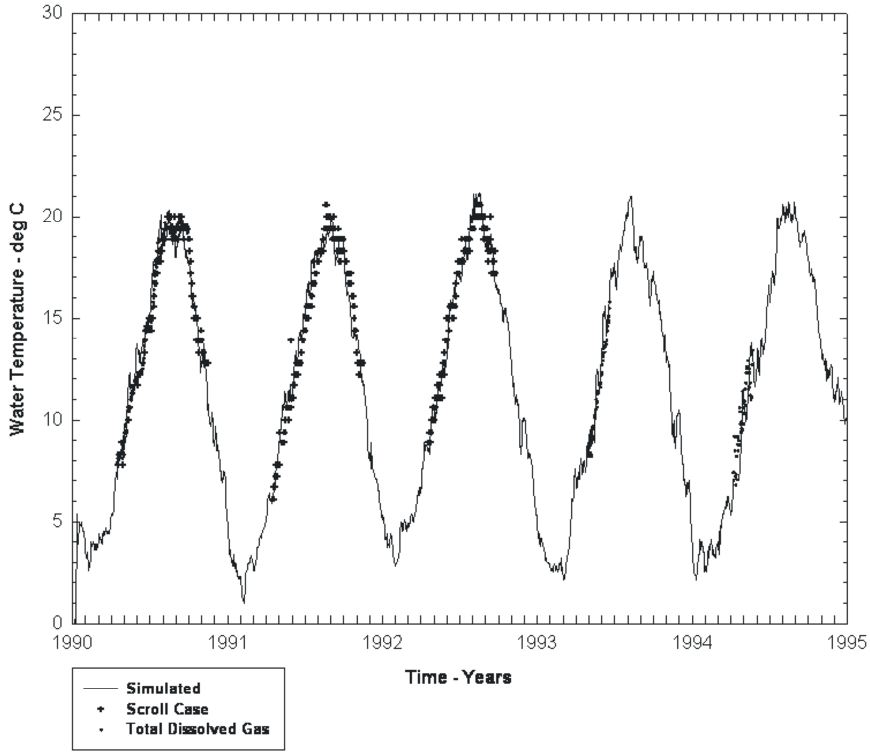

Figure 3-5. Simulated and observed water temperatures at Priest Rapids Dam for the period 1990–1994.

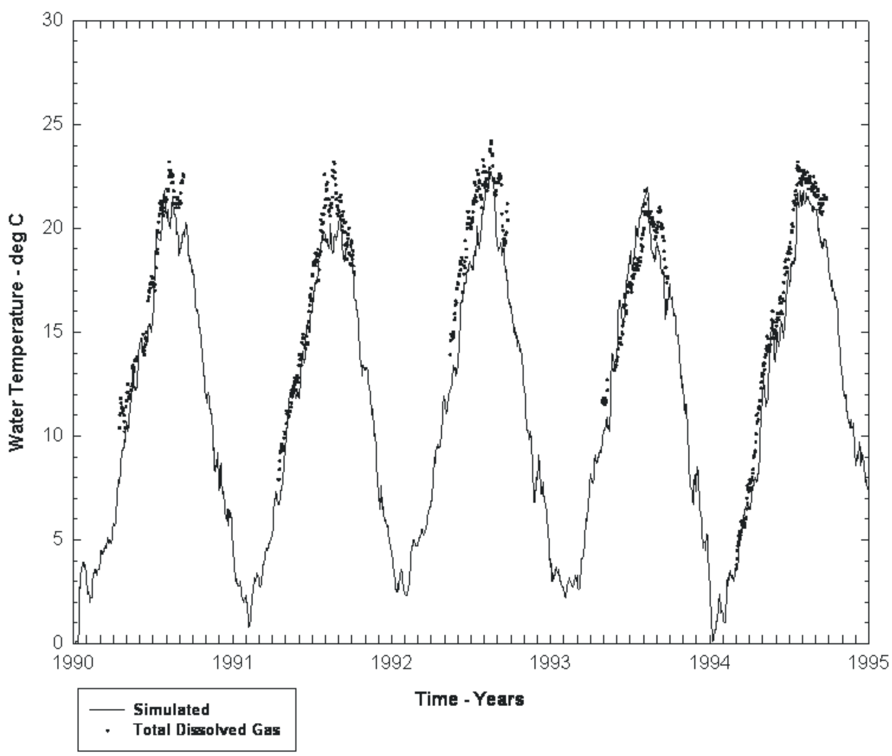

Figure 3-6. Simulated and observed water temperatures at McNary Dam for the period 1990–1994.

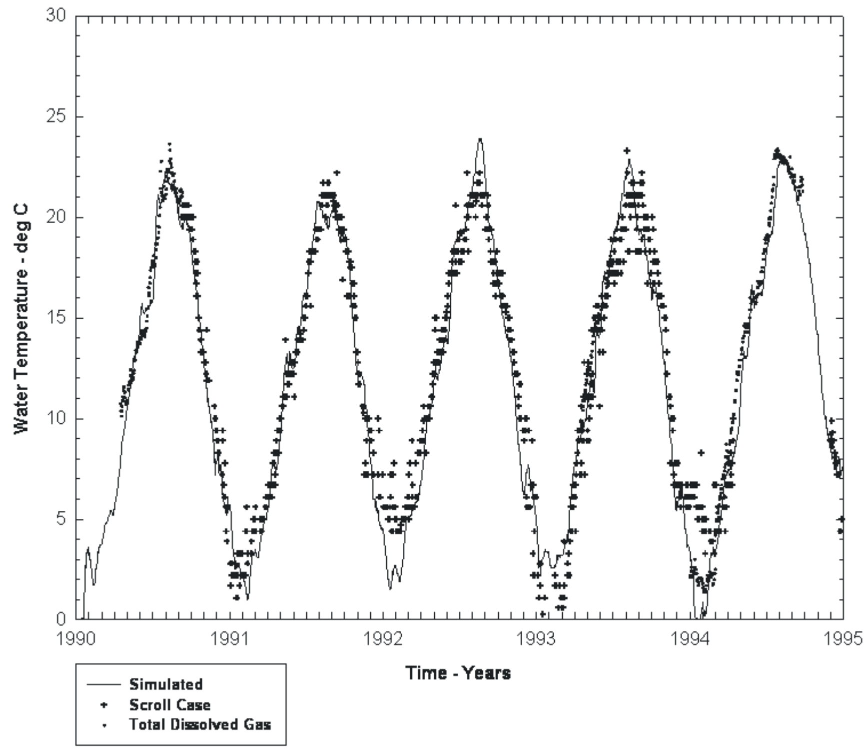

Figure 3-7. Simulated and observed water temperatures at John Day Dam for the period 1990–1994.

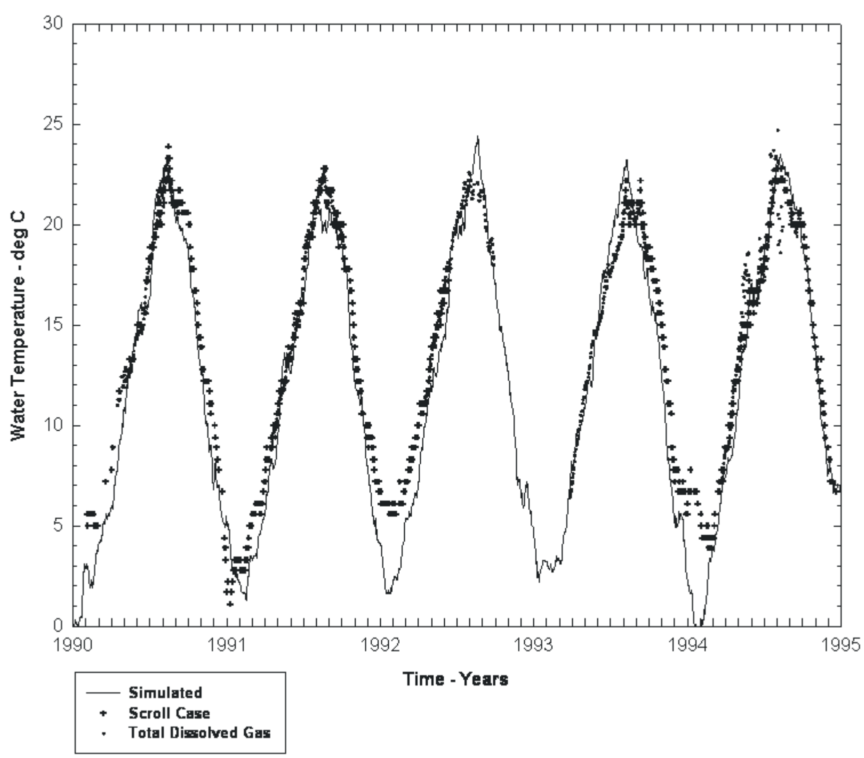

Figure 3-8. Simulated and observed water temperatures at Bonneville Dam for the period 1990–1994.

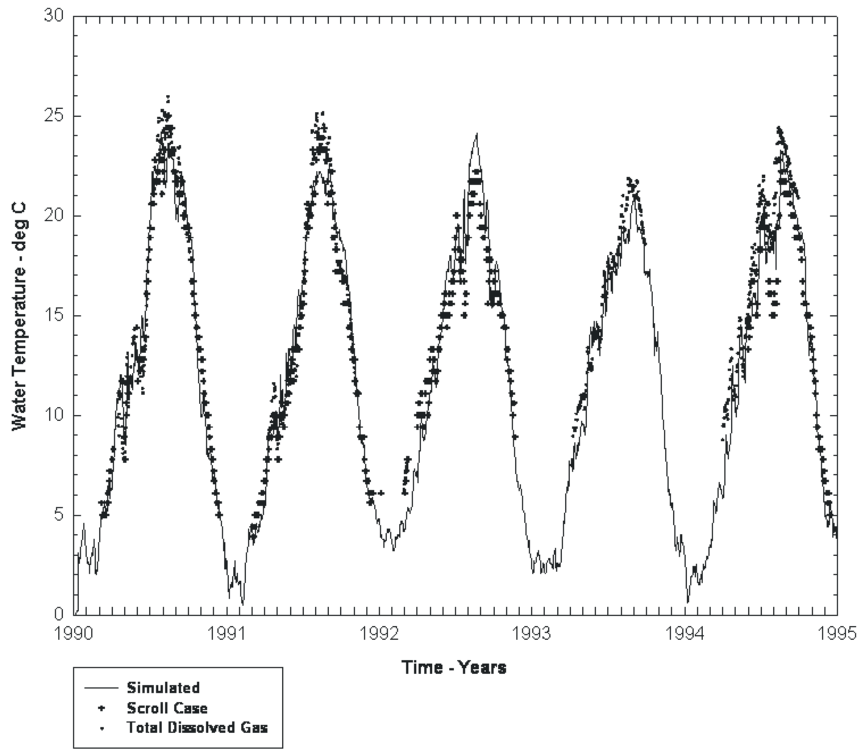

Figure 3-9. Simulated and observed water temperatures at Lower Granite Dam for the period 1990–1994.

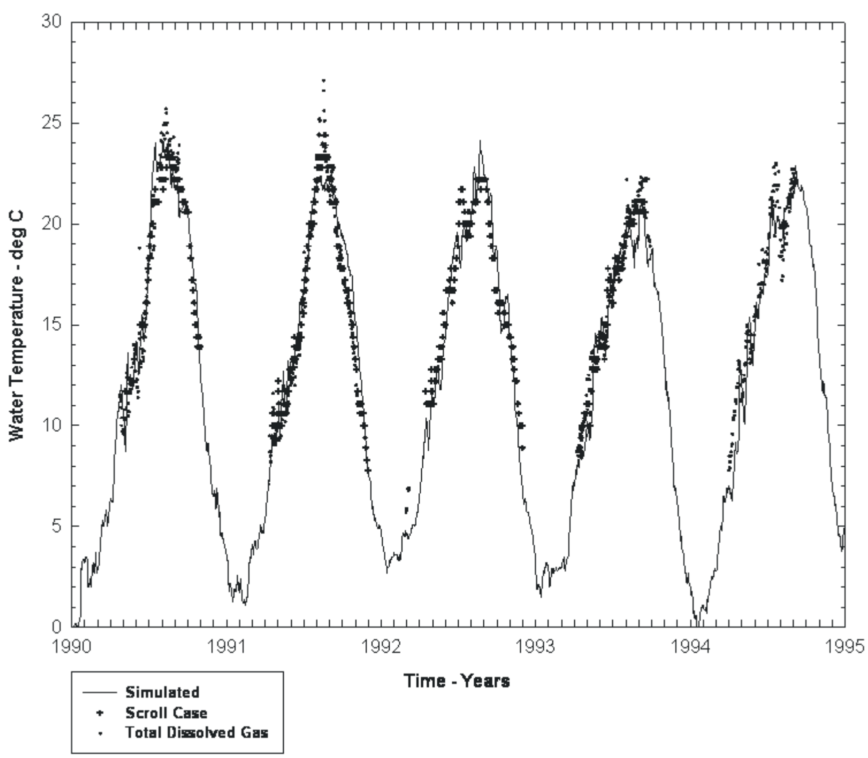

Figure 3-10. Simulated and observed water temperatures at Little Goose Dam for the period 1990–1994.

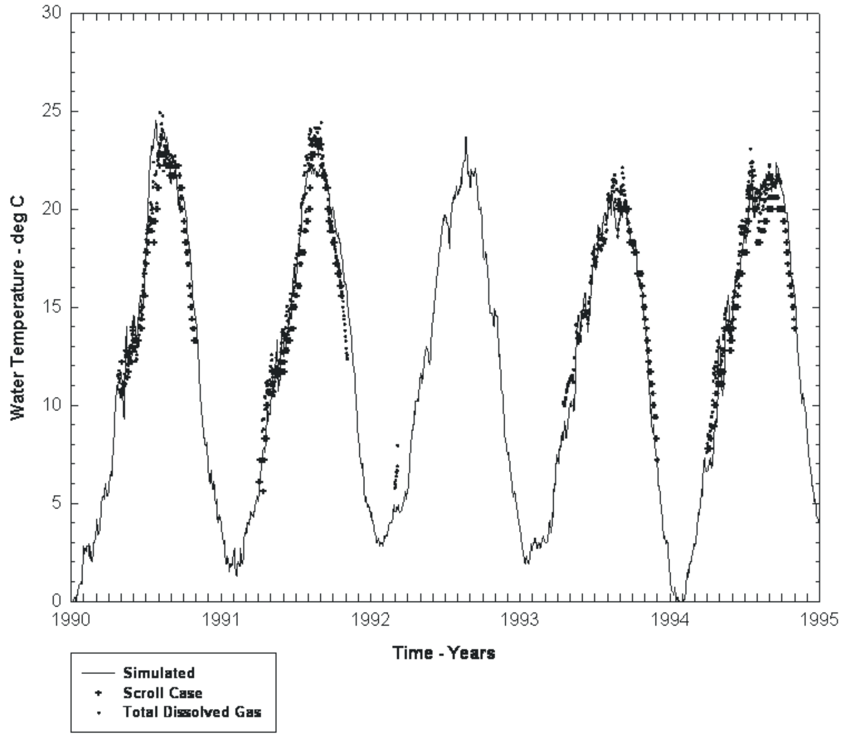

Figure 3-11. Simulated and observed water temperatures at Lower Monumental Dam for the period 1990–1994.

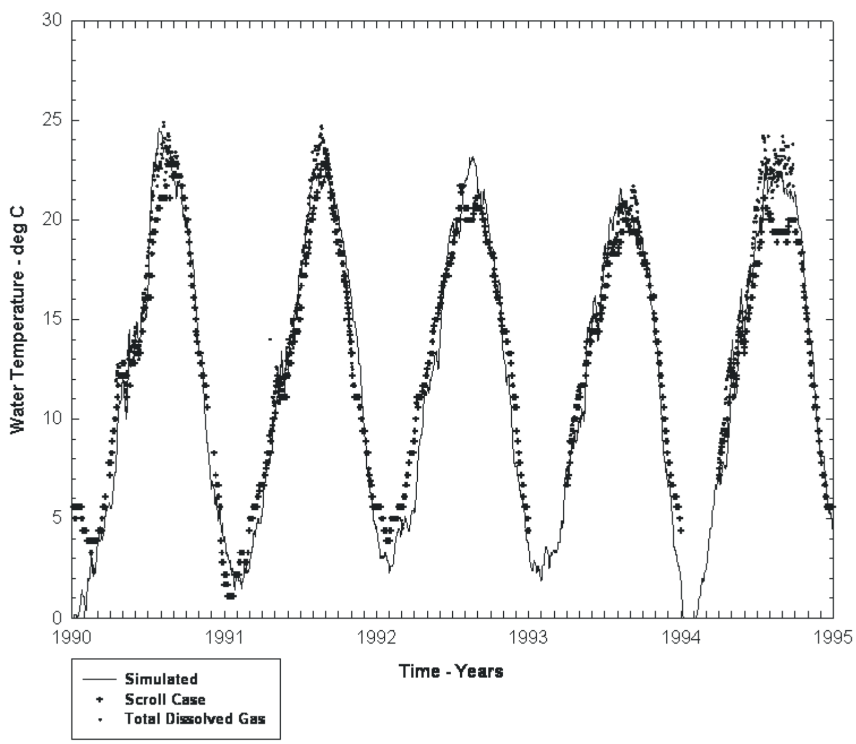

Figure 3-12. Simulated and observed water temperatures at Ice Harbor Dam for the period 1990–1994.

3.6 MODEL APPLICATION

Scenarios

The objectives of this study are to assess the relative contribution of impoundments and tributary inputs to changes in the thermal regime of the Columbia and Snake rivers. To capture the environmental variability in hydrology and meteorology, the 21-year record of stream flows and weather data from 1975 to 1995 is used to characterize river hydraulics and surface heat transfer rates. Most tributary temperatures are developed from local air temperatures using the relationship given by Equation 25 and air temperature data for the same 21-year period. The period from 1975 to 1995 was chosen to represent a period of relatively consistent management of the hydroelectric system. This assumption was based on the fact that it includes the period for which all the dams that are presently installed have been in operation. However, the assumption is confounded to a degree by the change in operation of Dworshak Dam beginning in the summer of 1992. Selective withdrawal of cold water at Dworshak Dam, beginning in 1992, has led to modifications in the temperature regime of the Snake River (Karr et al., 1998). For the period 1992-1995, measured temperatures at Dworshak Dam and at Orofino, Idaho, were used to account for the effects of selective withdrawal at Dworshak Dam.

The assessment of impacts to the thermal regime of the Columbia and Snake River is based on the following three scenarios:

Scenario 1 This scenario includes the existing configuration of dams, hydrology, and meteorology from 1975 to 1995 and tributary temperatures estimated from the 21-year meteorologic record using Equation 25.

Scenario 2 This scenario assumes the Columbia River downstream from Grand Coulee and the Snake River downstream from Lewiston, Idaho, are unimpounded and that hydrology, meteorology, and tributary temperatures are the same as Scenario 1.

Scenario 3 This scenario assumes the existing configuration of dams, with hydrology and meteorology for the period 1975 to 1995. Tributary input temperatures are estimated from the 21-year meteorologic record using Equation 25, but are not allowed to exceed 16 ^oC (60.8 ^oF).

For each of these scenarios, daily average water temperatures are simulated and the mean, mean plus one standard deviation, and the mean minus one standard deviation of the simulated water temperatures are compared to the benchmark, 20 ^oC (68 ^oF). Temperature excursions are defined for the three conditions as follows:

$$T^i_{ex} = T^i_{sim} - 20 \quad \text{for} \quad T^i_{sim} > 20$$

$$= 0 \quad \text{for} \quad T^i_{sim} < 20$$

where

T^1_{sim} = the simulated daily average water temperature – one standard deviation

T^2_{sim} = the simulated daily average water temperature

T^3_{sim} = the simulated daily average water temperature + one standard deviation

The average annual duration, or frequency, f^i_{ex}, of temperature excursions is estimated as the number of days in excess of the benchmark compared to the total number of days in the simulation. That is,

$$f_{ex}^{i} = \frac{\sum \delta_{ex}^{i}}{N}$$

where

$$\delta_{ex}^{i} = 1 \quad \text{for } T_{ex}^{i} > 20$$

$$= 0 \quad \text{for } T_{ex}^{i} < 20.$$

N = total number of days simulated

The standard deviation for these simulations is computed with the Kalman filter (Equations 10 to 17) in the prediction mode. In the prediction mode, the measurement matrix, H, is set to zero. This means the Kalman gain, K, is always zero and the variance propagation is a result of updating by the systems model only:

$$\Sigma_k = f_{k-1} P_{k-1} f_{k-1}^{T} + \Sigma_Q$$

where the (+) and (-) convention has been dropped since there is no updating based on the observations.

The frequencies of temperature excursions for each scenario as a function of Columbia and Snake River Mile are shown in Figures 3-13 to 3-18. The error bars in each of the plots represent the frequencies estimated with the simulated means plus one standard deviation and the simulated means minus one standard deviation.

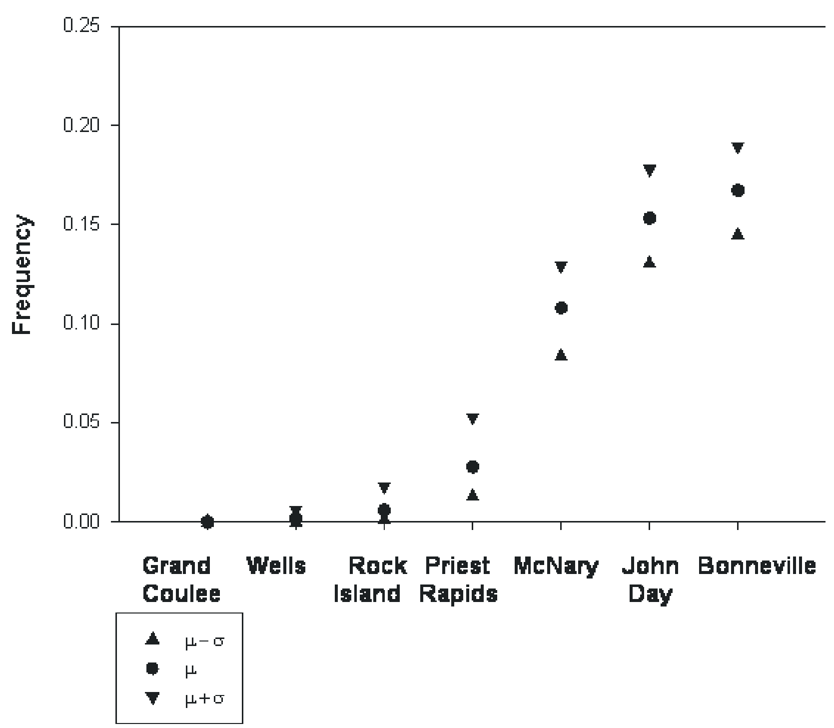

Figure 3-13. Frequency of predicted water temperature excursions in the Columbia River with dams in place.

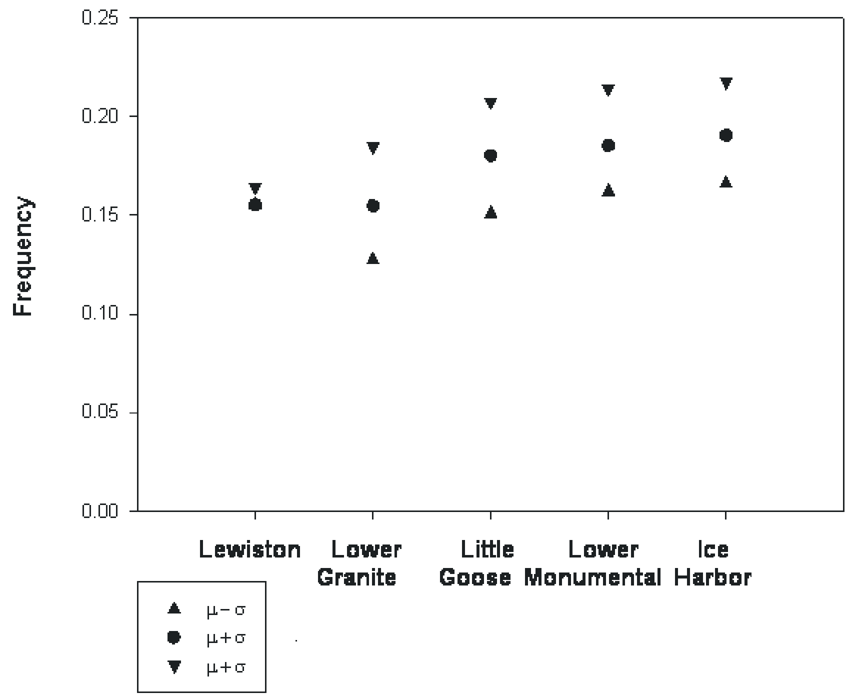

Figure 3-14. Frequency of predicted water temperature excursions in the Snake River with dams in place.

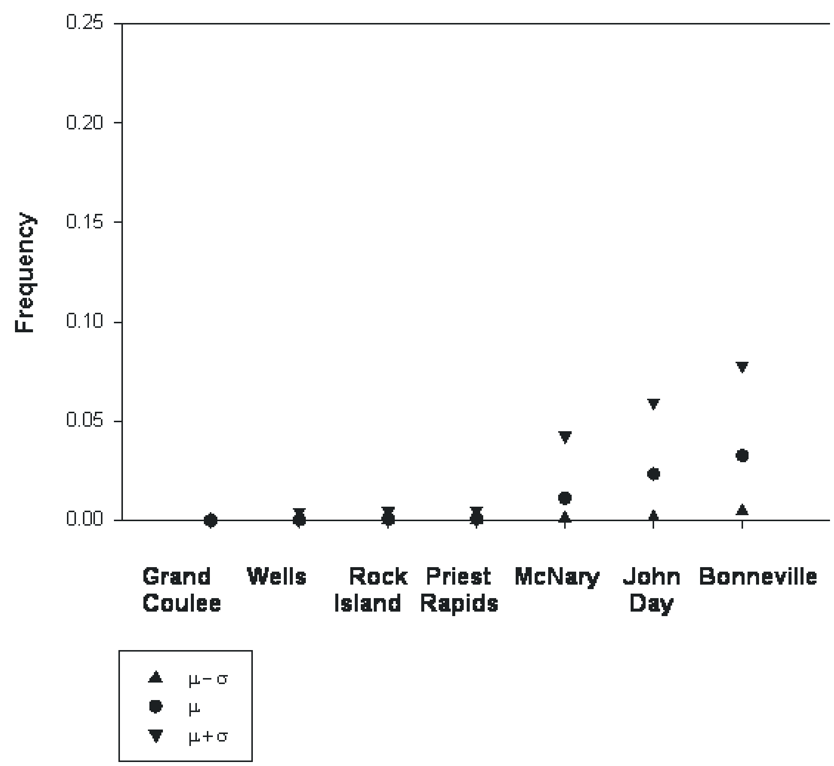

Figure 3-15. Frequency of predicted water temperature excursions in the Columbia River for the unimpounded river.

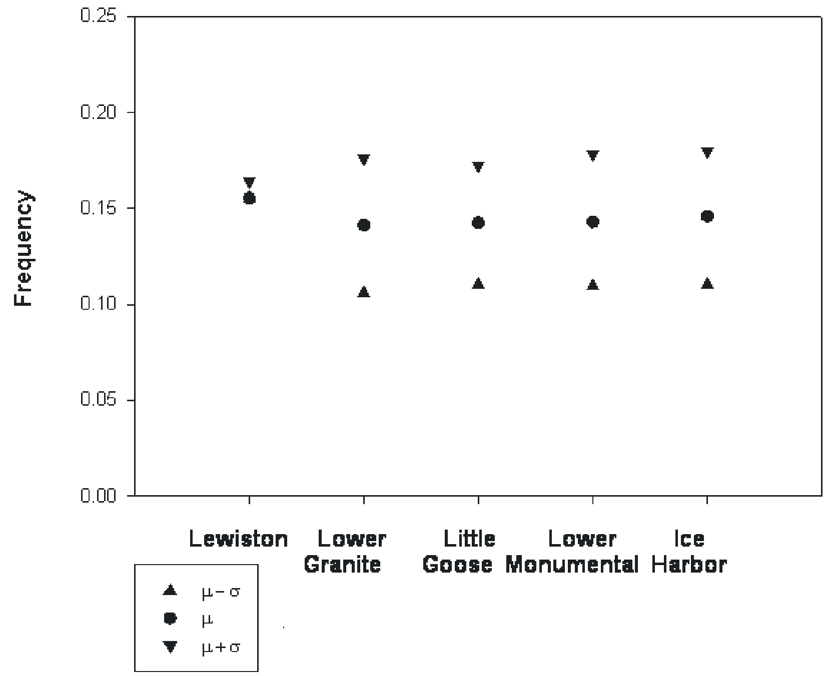

Figure 3-16. Frequency of predicted water temperature excursions in the Snake River for the unimpounded river.

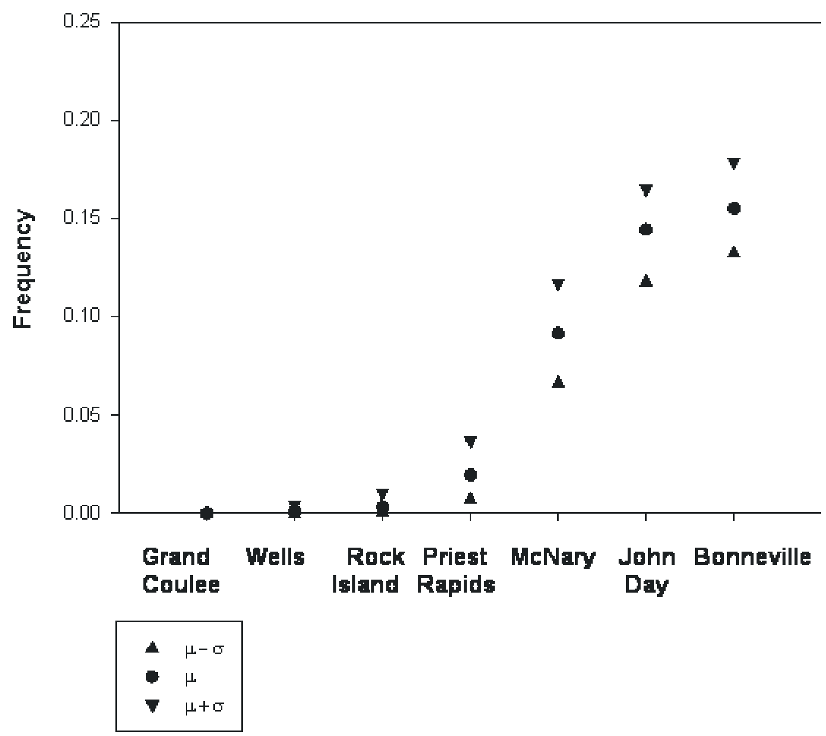

Figure 3-17. Frequency of predicted water temperature excursions in the Columbia River with dams in place and tributaries equal to or less than 16 °C.

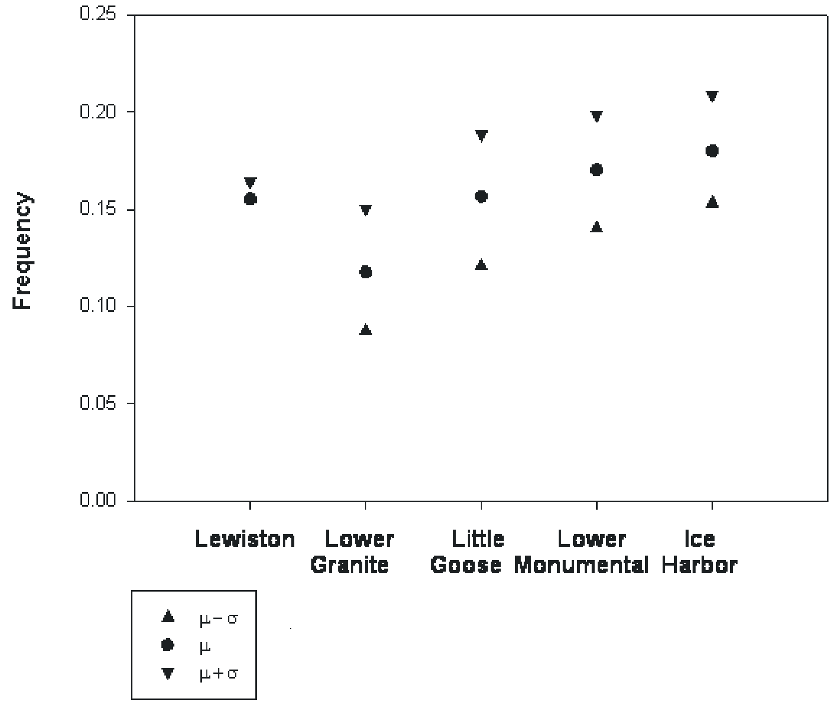

Figure 3-18. Frequency of predicted water temperature excursions in the Snake River with dams in place and tributaries equal to or less than 16 °C.

Results

The frequency of temperature excursions, calculated from the mean state estimates, establish a basis for assessing the relative impact of dams and tributary inflow on the thermal regime of the Columbia and Snake rivers. The frequency of temperature excursions, calculated from the mean plus and minus one standard deviation of the state estimates, provide the basis for assessing the significance of differences between scenarios. In this report, the significance of differences is discussed in a qualitative way only. A quantitative discussion of significance is usually done in the context of hypothesis testing or decisionmaking under uncertainty. Although one might argue that this temperature assessment is a form of decisionmaking under uncertainty, it has been treated in this report as part of the problem formulation for watershed planning under Section 303 (d) of the Clean Water Act. Implicit in this view of the temperature assessment is the notion that use of this methodology as a decisionmaking tool may require additional efforts to reduce uncertainty, as well as the development of formal statements or protocols regarding acceptable levels of risk.

For the Columbia River in Scenario 1, the existing conditions with dams in place, the mean annual frequency of temperature excursions increases from near zero at Grand Coulee Dam to somewhat greater than 0.03 at Priest Rapids. The influence of the warmer Snake River leads to an increase of the average frequency of excursions between Priest Rapids and McNary Dam from 0.03 to 0.11. Downstream from McNary Dam, the mean frequency of temperature excursions continues to increase to 0.17 at Bonneville Dam. The range of the frequency of excursions for the simulated average plus one standard deviation and the simulated average minus one standard deviation is of the order of ±0.03.

For the unimpounded case (Scenario 2), the mean annual frequency of excursions is approximately 0.03 at Bonneville Dam. The estimated uncertainty of the frequency increases slightly compared to the results of

Scenario 1, so that the frequencies of temperature excursion associated with the mean simulation plus one standard deviation are approximately 0.04 greater than that of the simulation. The increase in the uncertainty of the estimate for the river in the unimpounded scenario is due to the change in system dynamics associated with shallower depths and higher velocities. In spite of the increase in uncertainty, the difference in Scenarios 1 and 2 at those sites downstream from the confluence of the Snake River are clearly outside the bands defined by one standard deviation of the state estimates. In a qualitative sense, these differences are significant; that is, the unimpounded Columbia River has significantly fewer temperature excursions than does the impounded river. For the purposes of this assessment, however, no attempt has been made to evaluate the significance in terms of impact on the ecosystem.

The frequency properties of Scenario 3, for which tributary temperatures are constrained to be always less than 16 ^{o}C, are similar to Scenario 1 on the Columbia River upstream of its confluence with the Snake. The combined average annual flows of advected sources in this segment (Table 3-1) are less than 10 percent of average annual flow of the Columbia River at Grand Coulee Dam. The impact of these sources on the thermal energy budget of the main stem Columbia is, therefore, small. The 16 ^{o}C constraint was not applied to the Snake River and the warming effect of the Snake River on the Columbia is evident in the increase in the frequency of excursions between Priest Rapids Dam and McNary Dam. The net result being that frequency of excursions is not significantly different between Scenarios 1 and 3.

In the Snake River, with dams in place (Figure 3-14), the mean frequency of temperature excursions is relatively high (0.15) at the starting point (Snake River Miles 168.0), drops slightly due to the influence of the Clearwater River, then increases to 0.19 between there and Ice Harbor Dam (Snake River Miles 9.0). Because the Snake is a smaller river, it responds more rapidly to changes in systems dynamics. This, in turn, leads to larger uncertainty in the estimates as reflected in increased ranges of both frequency and magnitude of excursions. For the unimpounded case (Figure 3-16), the analysis predicts that the mean frequency of temperature excursions at Ice Harbor is approximately the same as the initial point near Anatone, Washington. The Clearwater River has a noticeable impact on water temperatures of the Snake River as shown by the reduction in the mean frequencies of temperature excursions for Scenarios 2 and 3 at Lower Granite Dam compared to the initial conditions for the Snake River at Anatone, Washington.

The wider bands of uncertainty reduce the significance of the results for the Snake River scenarios in the estimated frequency and magnitude of temperature excursions. At Lower Granite Dam, the differences in the three scenarios are small and within the uncertainty bands defined by one standard deviation of the state estimates. The qualitative level of significance in differences between Scenarios 1 and 2 increases downstream. At Ice Harbor Dam, the mean values of the frequency estimates for Scenario 2 are outside the uncertainty bands defined by one standard deviation of the state estimates of Scenario 1. Differences between Scenarios 1 and 3 are significant only at Lower Granite, where the impact of lower temperatures in the Clearwater River is still important.

Changes in cross-sectional daily average water temperature between initial conditions and some downstream point in rivers are due to (1) meteorology (wind speed, air temperature, cloud cover, air moisture content), (2) river depth, and (3) travel time between the two points. The meteorology determines the maximum temperature the water body can achieve; the depth and certain components of meteorology determine the rate at which the water body exchanges heat with the atmosphere; and the travel time determines the importance of initial conditions.

Some limits on the cross-sectional daily average water temperature in rivers can be estimated by defining the equilibrium temperature as the temperature a body of water would reach after very long exposure to a specific set of meteorological conditions. For a river moving with an infinitely high speed, the cross-sectional daily average water temperature at some downstream point will be exactly the same as the initial conditions. The meteorology would have no effect on cross-sectional daily average water temperature for this case. A water body at rest (no velocity) under constant meteorological conditions would eventually reach the equilibrium temperature determined by wind speed, air temperature, cloud cover, and air moisture content. The water depth and certain components of the meteorology would determine the time it takes to reach the equilibrium temperature.

The impact of structural changes on the cross-sectional daily average water temperature river system, such as the construction and operation of dams and reservoirs, is determined by the relative importance of the three factors described above. The results for Scenarios 1 and 2 imply that the structural changes associated with construction and operation of hydroelectric facilities on the Columbia and Snake rivers have led to changes in the travel times that are sufficient to modify the temperature regimes of these rivers.

The impact of advected sources such as tributaries and point discharges on the cross-sectional daily average water temperature of the main stem Columbia and Snake rivers is determined by the ratio of advected energy from the source ($\rho C_p Q_{adv} T_{adv}$) to the advected energy of the main stem ($\rho C_p Q_{main} T_{main}$). Contribution of thermal energy of most of the advected sources (Table 9) is small due to the magnitude of their flow compared to the main stems. The Clearwater River does have a significant cooling effect on the cross-sectional daily average water temperature of the Snake River. In addition, the Snake River has a significant warming effect on the cross-sectional daily average water temperature of the Columbia River.

CHAPTER 4: MODEL INPUT AND OUTPUT FILES

4.1 INPUT FILES

The Columbia River Temperature model requires three types of input files: the control file, advected source file, and meteorological file. The main input file, or control file, contains general model and reach information and lists which weather station files the model will use. The advected source file contains daily flow and temperature values for the main reaches as well as all the tributary inputs. The meteorological file contains data about each weather station that is used in the model.

The input files are divided into sections. Each section pertains to a general group of data. The sections are as follows:

Control File
Section 1 – General Model Information
Section 2 – Reach Information
Section 3 – Weather Station (Meteorological) File Names

Advected Source File
Section 4 – Input File Information for Advected Source File

Meteorological File
Section 5 – Input File Information for Meteorological File

Each section is made up of one or more records. A record contains data for a specific portion of that section. Each record is then defined by one or more lines of data. A detailed description of the input data structure for the input files follows.

Control File

An example of a control file is shown in Figure 4-1.

Section 1 (General Model Information)

Record 10 (General Model Information)

Line 1 advected source file name (i.e., crtass.adv)

Name of file that contains advected thermal energy data (flow and temperature) for main river stems and tributaries. In this model, there are three main river stems (Clearwater River, Snake River, and Columbia River) and 12 tributaries.

Line 2 model description

Description of Temperature Model

Line 3 model title

Temperature Model Title

Line 4 model start date, model end date

Date that model will begin and end computations. Format for each date is YYYYMMDD.

```
*************** INPUT FILE - CRTES.INP - FOR RBM10 ***************
*************** SECTION 1 - GENERAL MODEL INFORMATION ***************
R10.L1 crtass.adv
R10.L2 Reverse Particle Tracking Model-Existing Conditions-add Clearwater R
R10.L3 Columbia River Temperature Assessment Project - EPA Region 10
R10.L4   19750101  19951231        2
R10.L5 Number of reaches
R10.L6          3
*************** SECTION 2 - REACH INFORMATION ***************
*************** REACH 1 - CLEARWATER RIVER ***************
R20.L1 Clearwater River            4         5
R20.L2  40.0 30.0 20.0 10.0  5.0

R21.L1 Abv NF Confluence        RIVER           42.0 40.6 980.0000.
R21.L2     2    3    0    0    0
R21.L3     4.1693     0.693    56.765     0.233
R21.L4 End of Segment #A

R22.L1 Blw NF Confluence 1      RIVER           40.6 11.9 900.
R22.L2    30    3    0    1    0
R22.L3      4.053     0.693    56.234     0.233
R22.L4 Tributary Inflows
R22.L5 NF Clearwater R    1NFclr      40.1    9640.0
R22.L6 End of Segment #B
*************** REACH 2 - SNAKE RIVER ***************
R20.L1 Snake River                 49        5
R20.L2  168. 107. 70.5 41.7 10.1

R21.L1 Hells Canyon Reach       RIVER          168.7150.0 812.0000.
R21.L2     9    3    0    0    0
R21.L3      4.222     0.693    57.005     0.233
R21.L4 End of Segment #A

R22.L1 Hells Canyon Reach       RIVER          144.0140.0 760.
R22.L2     2    3    0    1    1
R22.L3      4.169     0.693    56.764     0.233
R22.L4 Tributary Inflows
R22.L5 Clearwater R.      2clear     140.1    9640.0
R22.L6 End of Segment #C

R24.L1 Lower Granite Resrvr     RSRVR          140.0137.3 746.
R24.L2     2    3    0    1    0
R24.L3     20825.     597.4       2.7   Volume (acre-feet) and Area (acres) in Seg 1
R24.L4 Tributary Inflows
R24.L5 Potlatch Corp      3potlt     139.5
R24.L6 End of Segment #1
*************** REACH 3 - COLUMBIA RIVER ***************
R20.L1 Columbia River              56        7
R20.L2  516. 474. 397. 292. 216. 192. 146.

R21.L1 Head of Chief Joseph     RIVER          596.1593.31000.
R21.L2     1    1    0    0    0
R21.L3     2.6338    0.7352   18.0219    0.3374
R21.L4 End of Segment #1

R24.L1 Wells Reservoir   #1     RSRVR          539.2533.3 803.
R24.L2     1    1    0    1    0
R24.L3    33809.6     1571.       5.9   Volume (acre-feet) and Area (acres) in Seg 1
R24.L4 Tributary Inflow
R24.L5 Okanogan River     6okngn     533.3    8340.0
R24.L6 End of Segment #13

R22.L1 Hanford Reach #13        RIVER          329.4324.0 450.  0.0  0.0
R22.L2     1    2    0    1    2
R22.L3    94.4921    0.5597 1585.1760    0.1194
R22.L4 Tributary Inflow
R22.L5 Snake River       12  sna     324.0   109000.
R22.L6 End of Segment #41

R23.L1 Bonneville Reservoir     RSRVR          165.7145.5  82.  0.0  0.0
R23.L2     7    4    0    0    0
R23.L3    285538.     9072.      20.2   Volume (acre-feet) and Area (acres) in Seg 2
R23.L4 End of Segment #56
*************** SECTION 3 - WEATHER STATION FILES AND EVAPORATION COEFFICIENTS ***************
R30.L1 wnatchee.hot                     1.55e-9
R30.L1 yakima.hot                       1.40e-9
R30.L1 lewiston.hot                     1.45e-9
R30.L1 richland.hot                     1.10e-9
```

Figure 4-1. Example control file.

Line 5 comment line

Line 6 number of reaches

This is the number of river reaches that are being modeled. In this model there are three river reaches (Clearwater River, Snake River, and Columbia River).

Section 2 (Reach Information)

Record 20 (Reach Description)

Line 1 reach name, number of segments in reach, number of plots to be sent to output file

Line 2 location of plots with respect to River Mile

Record 21 (River Segment with no tributary inflow)

Line 1 segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation

Line 2 number of computational elements per segmentation, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated

There can be a maximum of 600 computational elements per reach. The reach number of the tributary in this case (no tributary inflow) should be zero.

Line 3 a area, b area, a width, b width

These are the hydraulic coefficients determined for each reach.

Line 4 end of record

Record 22 (River Segment with tributary inflow)

Line 1 segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation

Line 2 number of computational elements per segment, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated

There can be a maximum of 600 computational elements per reach. The tributary numbering system is tricky, particularly if the tributary is one that is being simulated. The number appearing on this line is the REACH NUMBER of the tributary, while the number appearing on line 5 below is the ORDINAL NUMBER for the tributary. As an example, the Snake River (REACH 2) is a tributary to the Columbia and is the 12th tributary in the order of tributaries. Therefore, to specify the Snake as a tributary, one would enter a "2" on line 2, and a "12" on line 5, below. The order in which simulated tributaries occur is also important. The main requirement is that tributaries must be simulated before the reach to which they are tributary is simulated.

Line 3 a area, b area, a width, b width

These are the hydraulic coefficients determined for each reach.

Line 4 comment line

Line 5 tributary name, designated tributary number (ordinal number), abbreviated tributary name, river mile at which tributary connects to main segment, square miles of the watershed associated with the tributary

The square miles of the watershed associated with the tributary is not used in the program at this point.

Line 6 end of record

Record 23 (Reservoir Segment with no tributary inflow)

Line 1 segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation

Line 2 number of computational elements per segmentation, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated

There can be a maximum of 600 computational elements per reach. The reach number of the tributary in this case (no tributary inflow) should be zero.

Line 3 reservoir volume, reservoir area, delta x

Line 4 end of record

Record 24 (Reservoir Segment with tributary inflow)

Line 1 segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation

Line 2 number of computational elements per segment, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated

There can be a maximum of 600 computational elements per reach. The tributary numbering system is tricky, particularly if the tributary is one that is being simulated. The number appearing on this line is the REACH NUMBER of the tributary, while the number appearing on line 5 below is the ORDINAL NUMBER for the tributary. As an example, the Snake River (REACH 2) is a tributary to the Columbia and is the 12th tributary in the order of tributaries. Therefore, to specify the Snake as a tributary, one would enter a "2" on line 2, and a "12" on line 5, below. The order in which simulated tributaries occur is also important. The main requirement is that tributaries must be simulated before the reach to which they are tributary is simulated.

Line 3 reservoir volume, reservoir area, delta x

Line 4 comment line

Line 5 tributary name, designated tributary number (ordinal number), abbreviated tributary name, river mile at which tributary connects to main segment, square miles of the watershed associated with the tributary

The square mileage of the watershed associated with the tributary is not used in the program at this point.

Line 6 end of record

Section 3 (Weather Station (Meteorological) File Names)

Record 30 (Weather Station File Name Information)

Line 1 weather station file name, evaporation coefficient

Advected Source File

An example of an advected source file is shown in Figure 4-2.

Section 4 (Input File Information for Advected Source File)

Record 40 (Input File Information for Advected Source File)

Line 1 model start date, model end date

Record 41 (Advected Source Data for Each Julian Day)

Line 1	year, Julian day, flow for Clearwater River (cfs), water temperature for Clearwater River (deg-C), flow for Snake River (cfs), water temperature for Snake River (deg-C), flow for Columbia River (cfs), water temperature for Columbia River (deg-C)	
Line 2	NF of Clearwater River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 3	Potlatch Corp:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 4	Tucannon River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 5	Palouse River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 6	Okanogan River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 7	Methow River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 8	Chelan River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 9	Wenatchee River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

```
*************** INPUT FILE - CRTASS.ADV - FOR RBM10 ************
*** SECTION 4 – INPUT FILE INFORMATION FOR ADVECTED SOURCE DATA ***
  19750101  19951231
 1975    1     1150.       6.6    24000.       3.9    95300.       6.2
    1    2890.0  6.6
    3      62.2 33.0
    4     138.0  3.4
    5     174.0  4.2
    6     894.0  2.0
    7     320.0  2.5
    8    2190.0  2.6
    9    1250.0  6.4
   10      30.0  3.2
   11    2860.0  4.1
   13     494.0  4.3
   14     451.0  4.8
   15    6560.0  4.6
 1975    2     1140.       5.6    23000.       3.6    94700.       5.7
    1    4990.0  5.6
    3      62.2 33.0
    4     136.0  3.5
    5     167.0  3.9
    6     866.0  1.9
    7     330.0  2.3
    8    2180.0  2.6
    9    1180.0  5.3
   10      29.0  3.3
   11    2750.0  3.9
   13     482.0  4.1
   14     416.0  4.6
   15    6560.0  4.6
 1975    3     1430.       4.8    25000.       3.3    93000.       5.3
    1    7090.0  4.8
    3      62.2 33.0
    4     136.0  3.5
    5     172.0  3.7
    6     793.0  1.8
    7     330.0  2.1
    8    2180.0  2.6
    9    1160.0  4.5
   10      28.0  3.4
   11    2700.0  3.7
   13     462.0  3.9
   14     451.0  4.5
   15    6490.0  4.5
 1975    4     1500.       4.2    26800.       3.3   104000.       5.5
    1    7070.0  4.2
    3      62.2 33.0
    4     167.0  3.6
    5     282.0  3.5
    6     932.0  1.7
    7     340.0  2.0
    8    2180.0  2.6
    9    1160.0  3.8
   10      30.0  3.5
   11    2730.0  3.6
   13     482.0  3.7
   14     375.0  4.4
   15    6560.0  4.5
```

Figure 4-2. Example advected source file.

Line 10	Crab Creek:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 11	Yakima River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 12	Walla Walla:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 13	John Day River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 14	Deschutes River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Meteorological File

An example of a meteorological file is shown in Figure 4-3.

```
********** YAKIMA WEATHER DATA FROM HOURLY MEAN WDM DATA **********
***** SECTION 5 - INPUT FILE INFORMATION FOR METEOROLOGICAL FILE *****
YAKIMA AIR TERMINAL
         1     2000.       47.      121.  19750101  19951231
   1   0.01556   0.05185   1.16667   2.90580   0.65531   4.62069   0.05000
   2   0.00917   0.04683  -3.38889   2.14582   0.65250   3.87065   0.05000
   3   0.01056   0.05717   1.38889   2.32464   0.65545   5.06278   0.05000
   4   0.01472   0.05598   1.11111   4.20223   0.65527   4.89787   0.05000
   5   0.01500   0.05373   1.38889   3.48695   0.65545   5.77268   0.05000
   6   0.01444   0.05612   1.11111   2.63757   0.65527   4.85739   0.05000
   7   0.01000   0.05278  -2.83333   2.19052   0.65284   4.23095   0.05000
   8   0.01194   0.05350   1.27778   5.72218   0.65538   4.50621   0.05000
   9   0.01000   0.05152  -3.33333   3.21873   0.65253   3.47740   0.05000
  10   0.01833   0.04228  -7.94444   2.59286   0.64971   2.80806   0.05000
  11   0.00972   0.04945  -7.00000   2.54816   0.65029   2.74667   0.05000
  12   0.01194   0.04960  -6.61111   2.14582   0.65052   2.82048   0.05000
  13   0.01000   0.05516  -2.11111   1.29643   0.65328   4.41275   0.05000
  14   0.00972   0.05800   0.16667   0.89409   0.65469   5.54193   0.05000
  15   0.01278   0.06001   1.72222   2.10111   0.65565   5.29756   0.05000
  16   0.01194   0.05885   0.83333   0.75998   0.65510   5.34127   0.05000
  17   0.01222   0.05940   1.38889   2.32464   0.65545   5.89121   0.05000
  18   0.01944   0.05614   5.77778   3.48695   0.65818   7.05872   0.05000
  19   0.01306   0.05137  -0.33333   2.14582   0.65438   5.04190   0.05000
  20   0.01889   0.05849   6.66667   3.53166   0.65873   5.04190   0.05000
  21   0.01917   0.04951  -1.11111   2.27993   0.65390   4.05583   0.05000
  22   0.01000   0.05606  -0.11111   2.01170   0.65452   4.97972   0.05000
  23   0.01111   0.05710   1.44444   1.78818   0.65548   5.61028   0.05000
  24   0.00944   0.05991   2.55556   1.87759   0.65617   6.23463   0.05000
  25   0.01167   0.05907   1.00000   1.34114   0.65520   6.18451   0.05000
  26   0.02111   0.05234   0.11111   1.92230   0.65465   4.54409   0.05000
  27   0.02306   0.04568  -4.16667   3.08461   0.65202   3.17492   0.05000
  28   0.01528   0.05235  -3.94444   1.56466   0.65216   3.61468   0.05000
  29   0.01500   0.04988  -4.77778   2.19052   0.65165   3.38847   0.05000
  30   0.01306   0.05191  -4.83333   3.17402   0.65161   3.40315   0.05000
  31   0.01444   0.05375  -3.27778   2.95050   0.65257   3.53783   0.05000
  32   0.01389   0.05646  -1.05556   2.59286   0.65393   4.64001   0.05000
  33   0.01389   0.05536  -1.94444   1.92230   0.65339   4.23095   0.05000
  34   0.01389   0.05835   0.44444   1.87759   0.65486   5.14707   0.05000
  35   0.01500   0.05561  -0.72222   4.78339   0.65414   4.28478   0.05000
  36   0.01528   0.05304  -2.61111   4.96220   0.65298   3.16112   0.05000
  37   0.01639   0.05381  -3.22222   3.08461   0.65260   3.49242   0.05000
  38   0.02222   0.05130  -4.11111   1.56466   0.65205   3.56839   0.05000
  39   0.01639   0.05296  -3.94444   2.72698   0.65216   2.69842   0.05000
  40   0.02389   0.04909  -5.61111   2.50345   0.65114   3.16112   0.05000
  41   0.02833   0.04934  -1.72222   2.86109   0.65352   3.55308   0.05000
  42   0.01944   0.06050   4.22222   3.79989   0.65721   5.40743   0.05000
  43   0.01556   0.06309   6.16667   5.81159   0.65842   7.31533   0.05000
  44   0.02250   0.05747   4.22222   3.08461   0.65721   5.79621   0.05000
  45   0.02944   0.05142   1.61111   4.24693   0.65558   3.98760   0.05000
  46   0.01556   0.05005  -3.22222   2.50345   0.65260   3.70885   0.05000
  47   0.03194   0.04922  -0.72222   2.59286   0.65414   3.92039   0.05000
  48   0.02750   0.05098   0.27778   2.63757   0.65476   4.19540   0.05000
  49   0.01472   0.05966   1.72222   1.38584   0.65565   5.12588   0.05000
  50   0.01472   0.05984   3.00000   3.17402   0.65645   6.46463   0.05000
  51   0.02694   0.05153   1.33333   6.39275   0.65541   3.72475   0.05000
  52   0.03306   0.05173   1.16667   3.57636   0.65531   3.25886   0.05000
  53   0.02472   0.05581   2.22222   2.41405   0.65596   4.64001   0.05000
  54   0.02861   0.05922   3.00000   2.63757   0.65645   5.27583   0.05000
  55   0.03639   0.05435   4.27778   2.81639   0.65724   5.21110   0.05000
```

Figure 4-3. Example Meteorological File.

Section 5 (Input File Information for Meteorological File)

Record 50 (Input File Information for Meteorological File)

Line 1	weather station name

Line 2	nwpd, elevation of weather station, latitude of weather station, longitude of weather station, start date of weather station data, end date of weather station data

Record 51 (Weather Data for Each Day)

Line 1	Julian day, net solar radiation, Net atmospheric radiation, dry bulb temperature, wind speed, factor for Bowen ratio, vapor pressure at given air temperature, photo period *Photo period is not used in this model.*

4.2 OUTPUT FILES

An output file will be generated for each reach in the model. The number of output files is therefore specified in Record 10, Line 6. Data in the output file consist of daily average temperature and the standard deviation at each specified location. The number of sections within a reach to output data is located in Record 20, Line 1. The location of the output data, in river mile, is indicated in Record 20, Line 2. All output files contain the same format. An example of an output file is shown in Figure 4-4.

Column 1 of the output file is the decimal date out to three digits. The output from each station is then listed as three columns with the first column being the segment number, the second column being the standard deviation of the temperature in Deg C, and the third column being the absolute temperature in Deg C.

```
********** SAMPLE OUTPUT DATA FILE **********
1975.004     3     0   0.007     14     0   0.007     24     0   0.007
1975.006     3   5.3   0.031     14   5.1    0.13     24   4.9   0.227
1975.009     3   4.6   0.028     14   4.5   0.092     24   4.3   0.147
1975.012     3   4.2   0.028     14   4.1   0.095     24     4   0.154
1975.015     3   3.8   0.031     14   3.8   0.103     24   3.7   0.174
1975.017     3   3.4   0.084     14   3.3   0.132     24   3.3   0.229
1975.020     3   2.9   0.083     14   2.8   0.129     24   2.8   0.225
1975.023     3   2.7   0.028     14   2.6   0.098     24   2.6   0.161
1975.026     3     2   0.069     14   1.8   0.113     24   1.7   0.193
1975.028     3   1.8   0.125     14   1.7   0.136     24   1.6   0.239
1975.031     3   1.6   0.147     14   1.3   0.142     24     1   0.252
1975.034     3   1.5   0.166     14   1.2   0.096     24     1   0.136
1975.037     3   1.7   0.028     14   1.7   0.096     24   1.7   0.159
1975.039     3   1.6   0.182     14   1.7   0.162     24   1.7   0.295
1975.042     3   1.5    0.34     14   1.5    0.23     24   1.5   0.425
1975.045     3   1.5   0.301     14   1.5    0.19     24   1.5   0.339
1975.048     3   2.4   0.222     14   2.5   0.151     24   2.6   0.264
1975.050     3   3.9     0.1     14     4   0.112     24   4.1   0.186
1975.053     3   2.3   0.468     14   2.2   0.226     24   2.2   0.388
1975.056     3   2.8   0.313     14   2.8   0.162     24   2.8    0.27
1975.059     3   1.5   0.335     14   1.5   0.182     24   1.5   0.309
1975.061     3   2.1   0.133     14   2.1   0.113     24   2.1   0.184
1975.064     3     3   0.156     14     3   0.125     24     3   0.205
1975.067     3   2.1   0.372     14   2.1   0.222     24   2.2   0.386
1975.069     3   1.7   0.482     14   1.7   0.329     24   1.7   0.576
1975.072     3   0.6   0.144     14   0.6   0.116     24   0.7   0.188
1975.075     3   1.2   0.428     14   1.2    0.24     24   1.2   0.417
1975.078     3   1.3   0.425     14   1.3   0.247     24   1.2   0.446
1975.080     3   1.2   0.323     14   1.2    0.18     24   1.2   0.319
1975.083     3     1   0.152     14   0.7   0.128     24   0.5    0.22
1975.086     3     1   0.124     14   0.7    0.12     24   0.5   0.206
1975.089     3   1.4   0.104     14   1.4    0.12     24   1.4   0.207
1975.091     3   1.3    0.28     14   1.3   0.188     24   1.3    0.34
1975.094     3   1.2   0.372     14   1.2   0.205     24   1.2   0.371
1975.097     3     1   0.229     14     1   0.154     24     1   0.271
  1975.1     3   0.9    0.22     14   0.8    0.16     24   0.8   0.284
1975.102     3   0.9   0.207     14   0.7    0.16     24   0.6   0.285
1975.105     3   0.9   0.133     14   0.7   0.136     24   0.6   0.238
1975.108     3   0.9   0.302     14   0.8   0.199     24   0.8   0.363
1975.111     3   0.9   0.199     14   0.7   0.154     24   0.6   0.273
1975.113     3   1.1   0.192     14   1.1   0.164     24   1.1   0.294
1975.116     3   1.4   0.043     14   1.5   0.105     24   1.5   0.177
1975.119     3   1.6   0.169     14   1.7   0.145     24   1.8   0.255
1975.121     3   1.7   0.183     14   1.8   0.148     24   1.9   0.262
1975.124     3   1.6   0.189     14   1.6   0.157     24   1.7   0.278
1975.127     3   1.4   0.161     14   1.4   0.147     24   1.4   0.259
1975.130     3   1.4   0.167     14   1.4    0.15     24   1.4   0.264
1975.132     3   1.5   0.252     14   1.5   0.216     24   1.5   0.393
1975.135     3   1.5   0.144     14   1.5   0.145     24   1.5   0.256
1975.138     3   1.7     0.1     14   1.8   0.125     24   1.8   0.217
1975.141     3   1.4   0.027     14   1.4   0.099     24   1.3   0.164
1975.143     3   1.7   0.175     14   1.7   0.151     24   1.7   0.268
1975.146     3   1.7   0.097     14   1.7   0.125     24   1.7   0.218
1975.149     3     2   0.036     14   2.1   0.105     24   2.2   0.177
1975.152     3   2.4   0.133     14   2.5   0.128     24   2.6   0.223
1975.154     3   2.2   0.209     14   2.2   0.175     24   2.3   0.315
1975.157     3     2   0.157     14     2   0.152     24     2   0.268
1975.160     3   2.4   0.124     14   2.5   0.132     24   2.5   0.231
```

Figure 4-4. Example output file.

CHAPTER 5: STUDY SUMMARY AND CONCLUSIONS

The results of the analysis lead to the following conclusions:

- Structural changes in Columbia River downstream from Grand Coulee Dam and in the Snake River from its confluence with the Grande Ronde River to its confluence with the Columbia River near Pasco, Washington, cause an increase in mean frequency of water temperature excursions above a daily average water temperature of 20 ^{o}C. The structural changes are a result of the construction and operation of hydroelectric facilities on the Columbia and Snake rivers in the study area. This conclusion is based on a comparison of the mean frequency of temperature excursions for the system as presently configured and for the same system in the unimpounded condition. The unimpounded condition assumes there are no dams on the Columbia River below Grand Coulee and no dams on the Snake River below Lewiston, Idaho. The uncertainty in these estimates is approximately of the order of the estimated differences in the results, however. Improving both the systems and measurements models could reduce uncertainty. Actions could include improving the quality of water temperature observations, increasing the spatial coverage of required meteorological data, and studying the seasonal variations in certain terms of the heat budget, particularly the evaporation rate. The reduction in uncertainty would not affect the basic result that structural differences in the system due to the construction and operation of hydroelectric facilities have a greater impact on the temperature regime than does the thermal input from all of the major tributaries other than the Clearwater River.

- Most advected sources, including tributaries, groundwater and point sources, contribute a relatively small amount of advected thermal energy to of the main stem Columbia and Snake rivers in the study area. Their impact on the cross-sectional daily average water temperature is limited. The exceptions are the impact of the Clearwater River on the cross-sectional daily average water temperature of the Snake River and that of the Snake River on the cross-sectional daily average water temperature of the Columbia River.

- The objective of the analysis was to assess the relative impact of dams and tributaries on the temperature regime of the Columbia and Snake rivers. The impact of upstream inputs was limited to the characterization of initial temperature conditions at Grand Coulee Dam on the Columbia River and River Mile 168 on the Snake River. However, upstream inputs have an important role in the temperature regime of both rivers. In the Columbia River, construction of Canadian impoundments and the operation of Grand Coulee Dam affect the temperature of the Columbia River at Grand Coulee Dam, although the frequency of excursions are small at this location. For the Snake River, initial conditions near Anatone, Washington, are such that the mean frequency of temperature excursions is approximately 0.15. This is due to structural changes to the natural river upstream from Anatone, and to the river's exposure to high temperatures as it crosses the Snake River Plain. A larger geographical scope is needed to assess the impacts of water management in both the Columbia and Snake rivers.

Topics for Further Study

The results of this assessment lead to the conclusion that the construction and operation of dams on the Columbia River downstream from Grand Coulee Dam and on the Snake River downstream from Lewiston, Idaho, have a greater impact on the thermal regime of these rivers than do the thermal inputs form most of the tributaries. However, in the case of the Snake River, the significance of this conclusion is reduced by uncertainty in the mathematical model. Use of the model as a decision-making tool would require additional efforts to reduce this uncertainty. Elements of the model where reduction in uncertainty would be of benefit include the following:

- Heat budget – The choice of meteorological stations to characterize the energy budget was done subjectively, to achieve good (in a qualitative sense) agreement between simulated values and observations. The analysis would benefit from additional studies of the effect of local climatology, particularly wind speed.

- River hydraulics – Particle displacement speeds and system geometry were based on the assumption that gradually varied, steady-state flow methods were appropriate. This assumption is reasonable for the scenarios for which the dams are in place and less so for the river without dams. The uncertainties associated with rapidly changing flows are likely to be greatest during the spring and early summer snowmelt periods. It is less likely they will be important during the critical late summer and early fall periods when flows are low and reasonably steady.

- Initial water temperatures – Initial conditions for water temperature of both main stem and tributaries were estimated by synthesizing a record with data from various sources. The error introduced as a result is greatest for the main stem temperatures, since the results of the analysis show that the tributaries have little impact on the average temperatures of the Columbia and Snake rivers. The error introduced in the main strem estimates will decrease in the downstream direction.

- Filter – The estimation of the systems model error is based on the assumption the filter is optimal. The filter is optimal if the innovations sequence is a zero mean, Gaussian white noise process. Tests for optimality of the filter have been described by Mehra (1970). These tests were not performed on the water temperature innovations sequence due to the number of missing data points, but a visual inspection of the 30-day averages of the innovations sequence suggest the results are autocorrelated. This correction could be a result of structural errors in the model, as described above, or could be related to observation bias and error reported by McKenzie and Laenen (1998).

- Water temperature data – The water temperature monitoring program on the Columbia and Snake rivers has produced a large volume of data; however, the quality of the data is sometimes questionable. The analysis of water temperature issues on the Columbia and Snake rivers would benefit greatly from a comprehensive plan for measuring water temperatures.

REFERENCES

Baca, R.G., and R.C. Arnett. 1976. A finite element water quality model for eutrophic lakes. BN-SA-540. Battelle Pacific Northwest Lab., Richland, Washington.

Bartholow, J.M. 1989. *Stream temperature investigations—Field and analytic methods*. Instream Flow and Info. Paper No.13. U.S. Fish and Wildlife Service.

Beck, B., and P. Young. 1976. Systematic identification of DO-BOD model structure. *J. Environ. Eng., ASCE* 102 (EE5): 909-927.

Bonneville Power Administration et al. 1994. *Columbia River system operation review*. Appendix M, Water quality. DOE/EIS-0170. Bonneville Power Administration, U.S. Army Corps of Engineers, and U.S. Bureau of Reclamation, Portland, Oregon.

Bowie, G.L., W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W.H. Chan, and S.A. Gherini. 1985. *Rates, constants, and kinetics formulations in surface water quality modeling* (2nd ed). EPA/600/3-85-040. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia.

Bowles, D.S., and W.J. Grenney. 1978. Steady-state river quality modeling by sequential extended Kalman filter. *Water Resour. Res.* 14: 84-96.

Brown, G.W. 1969. Predicting temperatures of small streams. *Water Resour. Res.* 5(1), 68-75.

Brown, G.W. 1970. Predicting the effect of clear cutting on stream temperature. *J. Soil Water Conserv* 25: 11-13.

Brown, L.C., and T.O. Barnwell, Jr. 1987. *The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS*. EPA/600/3-87/007. U.S. Environmental Protection Agency, Environmental Resource Labratory, Athens, Georgia.

Burt, W.V. 1958. Heat budget terms for Middle Snake River Reservoir. In *Water temperature studies on the Snake River*, Tech. Rep. 6, U.S. Fish and Wildlife Serv, Washington, DC.

Chapra, S.C. 1997. *Surface water-quality modeling.* McGraw-Hill Companies, Inc., New York, New York.

Cheng, R.T., V. Casulli, and S.N. Milford. 1984. Eulerian-Lagrangian solution of the convection-dispersion equation in natural coordinates. *Water Resour. Res.* 20(7): 944-952.

Cole, T.M., and E.M. Buchak. 1995. *A two-dimensional laterally averaged, hydrodynamic and water quality model*. Version 2.0. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Coutant, C.C. 1999. *Perspectives on temperature in the Pacific Northwest's fresh waters*. Oak Ridge National Laboratory, Environmental. Science Division. Pub. No. 4849.

Dandy, G.C., and S.F. Moore. 1979. Water quality sampling programs in rivers. *J. Environ. Eng. Div., ASCE* 105: 695-712.

Davidson, F.A. 1964. The temperature regime of the Columbia River from Priest Rapids, Washington to the Arrow Lakes in British Columbia. Prepared for the Public Utility District No. 2 of Grant County, Ephrata, Washington.

Delay, W.H., and J. Seaders. 1966. Predicting temperature in rivers and reservoirs. *J. Sanit. Eng. Div. Am. Soc. Civ. Eng.* 92: 115-134.

Edinger, J.E., D.K. Brady, and J.C. Geyer. 1974. Heat exchange and transport in the environment. Report 14. Electric Power Resource Institute, Palo Alto, California.

Foreman, M.G.G., C.B. James, M.C. Quick, P. Hollemans, and E. Wiebe. 1997. Flow and temperature models for the Fraser and Thompson Rivers. *Atmosphere-Ocean* 35(1): 109-134.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979. *Mixing in inland and coastal waters*. Academic Press, New York, New York.

Gelb, A., J.F. Kasper, Jr., R.A. Nash, Jr., C.F. Price, and A.A. Sutherland, Jr. 1974. *Applied optimal estimation.* MIT Press, Cambridge, Massachusetts

Hansen, A.J., Jr., J.J. Vaccaro, and H.H. Bauer. 1994. *Ground-water flow simulation of the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho*. U.S. Geological Survey Water-Resources Investigations Report 91-4187. U.S. Geological Survey, Tacoma, Washington.

Harrison, J., S. Wells, R. Myers, and M. Kasch. 1999. 1999 Status report on Brownlee Reservoir water quality and model development. Draft technical report. Idaho Power Company, Boise, Idaho.

Henderson, F.M. 1966. *Open channel flow*. The Macmillan Company, New York, New York.

Hill, M.C. 1994. *Five computer programs for testing weighted residuals and calculating linear confidence and prediction intervals on results from the ground-water parameter-estimation computer program MODFLOWP*. U.S. Geological Survey Open-File Report 93-481. U.S. Geological Survey, Denver, Colorado.

Independent Scientific Group. 1996. *Return to the river: Restoration of salmonid fishes in the Columbia River ecosystem*. Northwest Power Planning Council, Portland, Oregon.

Jaske, R.T., and M.O. Synoground. 1970. *Effect of Hanford plant operations on the temperature of the Columbia River 1964 to present*. BNWL-1345. Battelle Northwest, Richland, Washington.

Jobson, H.E. 1981. *Temperature and solute-transport simulation in streamflow using a Lagrangian reference frame*. U.S. Geological Survey Water Resources Investigation Report No. 81-2. U.S. Geological Survey.

Kailath, T. 1968. An innovations approach to least squares estimation. Part I: Linear filtering in additive white noise. *IEEE Trans. Auto. Contr., AC-13*: 646-655.

Karr, M.H., J.K. Fryer, and P.R. Mundy. 1998. *Snake River water temperature control project—Phase II*. Columbia River Inter-Tribal Fish Commission. Portland, Oregon.

Kohler, M.A. 1954. Lake and pan evaporation. In *Water-loss investigations: Lake Hefner studies, technical report*, pp. 127-148. Geological Survey Professional Paper 269. U.S. Government Printing Office, Washington, DC.

Koivo, A.J., and G.R. Phillips. 1976. Optimal estimation of DO, BOD and stream parameters using a dynamic discrete time model. *Water Resour. Res*. 12: 705-711.

Leopold, L.B., and T. Maddock. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey Professional Paper 252. U.S. Geological Survey.

Lettenmaier, D.P. 1975. *Design of monitoring systems for detecting trends in stream quality*. Tech. report no. 39. C.W. Harris Hydraulics Laboratory, University of Washington, Seattle, Washington.

Lettenmaier, D.P., and S.J. Burges. 1976. Use of state estimation techniques in water resource systems modeling. *Water Res. Bull.* 12: 83-99.

Marciano, J.J. and G.E. Harbeck. 1952. Mass transfer studies in water loss investigations: Lake Hefner studies. USGS Prof. Paper 269.

Matalas, N.C., and T. Maddock III. 1976. Hydrologic semantics. *Water Resour. Res.* 12(1): 123-124.

McCullough, D.A. 1999. *A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to chinook salmon*. Prepared for U.S. EPA Region 10, Seattle, Washington.

McKenzie, S.W., and A. Laenen. 1998. *Assembly and data-quality review of available continuous water temperatures for the main stems of the lower- and mid-Columbia and lower-Snake rivers and mouths of major contributing tributaries*. NPPC Contract C98-002. Northwest Power Planning Council, Portland, Oregon.

Mehra, R.K. 1970. On the identification of variances and adaptive Kalman filtering. *IEEE Trans. Auto. Contr., AC-15:* 175-184.

Mehra, R.K. 1972. Approaches to adaptive filtering. *IEEE Trans. Auto. Contr., AC-17*: 693-698.

Mohseni, O., H.G. Stefan, and T.R. Erickson. 1998. A nonlinear regression model for weekly stream temperatures. *Water Resour. Res.* 34(10): 2685-2692.

Moore, A.M. 1969. *Water temperatures in the Columbia River basin—Water Year 1968.* Open-File Report. U.S. Geological Survey, Portland, Oregon.

Moore, S.F. 1973. Estimation theory application to design of water quality monitoring systems. *J. of the Hydraul. Div. Am. Soc. Civ. Eng.*, 99(HY5): 157-181.

Moore, S.F., G.C. Dandy, and R.J. deLucia, 1976. Describing variance with a simple water quality model and hypothetical sampling program. *Water Resour. Res.,* 12: 795-804.

Nelder, J.A., and R. Mead. 1965. A simplex method for function minimization. *Computing Jour.,* 7:308-313.

Normandeau Associates. 1999. Lower Snake River temperature and biological productivity modeling. R-16031.007. Preliminary review draft. Prepared for the Department of the Army, Corps of Engineers, Walla Walla, Washington.

O'Neill, K. 1981. Highly efficient, oscillation free solution of the transport equation over long times and large spaces. *Water Resour. Res.* 17(6): 1665-1675.

Oregon DEQ. 1998. Water quality limited streams 303(d) list. Oregon Department of Environmental Quality <http://waterquality.deq.state.or.us/wq/303dlist/303dpage.htm>.

Oreskes, N., K. Shrader-Frechette, K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263: 641-646.

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. 1986. *Numerical recipes: The art of scientific computing*. Cambridge University Press, New York, New York.

Rajaram, H., and K.P. Georgakakos. 1987. *Recursive parameter estimation of conceptual watershed response models.* IIHR Report No. 319. Iowa Institute of Hydraulic Research, Iowa City, Iowa.

Raphael, J.M. 1962. Prediction of temperature in rivers and reservoirs. *J. Power Div. ASCE,* (PO 2): 157-181.

Rishel, G.B., J.A. Lynch, and E.S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. *J. Environ. Qual.* 11(1): 112-116.

Risley, J.C. 1997. *Relations of Tualatin River water temperatures to natural and human-caused factors*. U.S. Geological Survey Water Resources Investigation Report 97-4071. U.S. Geological Survey.

Schweppe, F.C. 1973. *Uncertain dynamic systems.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Sinokrot, B.A., and H.G. Stefan. 1993. Stream temperature dynamics: Measurements and modeling, *Water Resour. Res.* 29(7): 2299-2312.

Smith, D.J. 1978. Water quality for river-reservoir systems. U.S. Army Corps of Engineers, Water Res. Support Center, Davis, California.

Theurer, F.D., K.A. Voos, and W.J. Miller. 1984. *Instream water temperature model*. FWS/OBS-84-15, U.S. Fish and Wildlife Service.

Thomann, R.V. 1982. Verification of water quality models. *J. Environ. Eng. Div., ASCE* 108: 923-940.

USACE-HEC (U.S. Army Corps of Engineers). 1995. *HEC-RAS: River analysis system*. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

Valocchi, A.J., and M. Malmstead. 1992. Accuracy of operator splitting for advection-dispersion-reaction problems. *Water Resour. Res.* 28(5): 1471-1476.

van der Heijde, P.K.M. 1990. Quality assurance in the development of groundwater models. In *Transferring models to users*. Proceedings AWRA Symposium, Denver, Colorado, November 5-8, 1990, pp. 97-109.

Van Geer, F.C., C.B.M. Testroet, Z. Yangxiao. 1991. Using Kalman filtering to improve and quantify the uncertainty of numerical groundwater simulations. I. The role of the system noise and its calibration. *Water Resour. Res.* 27(8): 1987-1994.

Washington DOE. 1998. Washington's final 1998 Section 303(d) list (impaired and threatened surface waters). Washington State Department of Ecology. <http://www.wa.gov/ecology/wq/303d/>.

Water Resources Engineers. 1968. *Prediction of thermal energy distribution in streams and reservoirs*. Prepared for the Department of Fish and Game, State of California, Walnut Creek, California.

Wunderlich, W.O., and R. Gras. 1967. Heat and mass transfer between a water surface and the atmosphere. Tennessee Valley Authority, Division of Water Cont. Planning, Norris, Tennessee.

Yearsley, J.R. 1969. A mathematical model for predicting temperatures in rivers and river-run reservoirs. Working Paper No. 65, Federal Water Pollution Control Agency, Portland, Oregon.

Yeh, G.T. 1990. A Lagrangian-Eulerian method with zoomable hidden fine-mesh approach to solving advection-dispersion equations. *Water Resour. Res.* 26(6), 1133-1144.

Zhang, R., K. Huang, and M.T. van Genuchten. 1993. An efficient Eulerian-Lagrangian method for solving solute transport problems in steady and transient flow fields. *Water Resour. Res.* 29(12): 4131-4138.

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Appendix A

Summary of Temperature Preference Ranges and Effects for Life Stages of Seven Species of Salmon and Trout

The information in this appendix was taken from a review of the State of Oregon standard for water temperature completed by Cara Berman, U.S. Environmental Protection Agency Region 10, on September 3, 1998.

Definitions (from McCullough 1999):

Optimum: The optimum temperature range provides for feeding activity, normal physiological response, and normal behavior. The optimum range is slightly wider than the growth range.

Preferred: The preferred temperature range is that which the organism most frequently inhabits when allowed to freely select temperatures in a thermal gradient. The final temperature preferendum is a preference made within 24 hours in a thermal gradient and is independent of acclimation temperature.

Lethal loading: Increased burden on metabolism that controls growth and activity. Lethal loading stress occurs over long periods (Brett et al. 1958).

Upper incipient lethal temperature: An exposure temperature, given a previous acclimation to a constant temperature, that 50 % of the fish can tolerate for 7 days. The **ultimate upper incipient lethal temperature** is the point where further increases in acclimation temperature results in no increase in temperature tolerated.

Upper lethal temperature: The temperature at which survival of a test group is 50 % in a 10 minute exposure, given a prior acclimation temperatures within the tolerance zone.

I. Sockeye Salmon

Adult migration:	7.2-15.6^{0}C (Bell 1986, Spence et al. 1996) 10^{0}C adult sockeye lost 7.5 % body weight and had visible fat reserves, at 16.2^{0}C they lost 12 % of their body weight and visible fat reserves were essentially depleted. Females with developing eggs lost more body weight than males; adverse gonadal development in females (Bouck et al. 1975) 21^{0}C migration inhibition (Beschta et al. 1987 from Major and Mighell 1966). Above 21^{0}C rising or stable temperatures blocked entry of fish from the Columbia River into the Okanagan River, WA; falling temperatures allowed migration to resume.
Spawning:	10.6-12.2^{0}C (Bell 1986, Spence et al. 1996)
Incubation:	4.4-13.5^{0}C (Combs 1965) 4.4-13.3^{0}C (Bell 1986, Spence et al. 1996) 10^{0}C (Dept of Fisheries Canada, International Pacific Salmon Fisheries Commission 1952) > 12.8^{0}C severe mortality (Dept of Fisheries Canada, International Pacific Salmon Fisheries Commission 1952; Combs 1965)
Rearing:	10-12.8^{0}C (Bell 1986) 10.6^{0}C (Huntsman 1942, Burgner 1991) 10.6-12.8^{0}C (Coutant 1977) 14.5^{0}C (Coutant 1977, Ferguson 1958, Huntsman 1942) 12-14^{0}C (Brett 1952) 11.2-14.6^{0}C preferred (Beschta et al. 1987) 15^{0}C optimum (Beschta et al. 1987)

Physiological optimum: 15^{0}C (Brett et al. 1958)

Smolt out-migration: 2-10^{0}C (Spence et al. 1996)

Terminates smolt out-migration: 12-14^{0}C (Brett et al. 1958)

II. Spring Chinook Salmon:

Adult migration: 3.3-13.3^{0}C (Bell 1986, Bjornn and Reiser 1991, Spence et al. 1996)
21^{0}C migration block (Temperature Subcommittee, DEQ 1995)

Spawning: 5.6-14.4^{0}C (Olson and Foster 1955)
5.6-13.9^{0}C (Bell 1986, Spence et al. 1996)
5.6-12.8^{0}C (Temperature Subcommittee, DEQ 1995)

Incubation: 5-14.4^{0}C (Bell 1986, Spence et al. 1996)
4.5-12.8^{0}C (Temperature Subcommittee, DEQ 1995)

Rearing: 11.7^{0}C (Coutant 1977, Ferguson 1958, Huntsman 1942)
10-12.8^{0}C (Bell 1986)
10-14.8^{0}C (Temperature Subcommittee, DEQ 1995)

Adult holding: 8-12.5^{0}C (Temperature Subcommittee, DEQ 1995)
13-15.5^{0}C pronounced mortality (Temperature Subcommittee, DEQ 1995)
6-14^{0}C optimal pre-spawning brood stock survival, maturation, and spawning (Marine 1992)

Smoltification and Out-migration: 3.3-12.2^{0}C (Temperature Subcommittee, DEQ 1995)
18.3^{0}C smolt lethal loading stress (Temperature Subcommittee, DEQ 1995)

Optimum production: 10^{0}C (Temperature Subcommittee, DEQ 1995)

Maximum growth: 14.8^{0}C (Temperature Subcommittee, DEQ 1995)

Lethal: 18-21^{0}C (Marine 1992)
17.5^{0}C - upper sub-lethal to lethal range (Berman 1990)

Sublethal: 15-17^{0}C (Marine 1992, Berman 1990)

III. Summer Chinook Salmon:

Adult Migration: 13.9-20^{0}C (Bell 1986, Spence et al 1996)

Spawning: 5.6-14.4^{0}C (Olson and Foster 1955)
6.1-18.0^{0}C (Olson and Foster 1955)
5.6-13.9^{0}C (Spence et al. 1996)

Incubation: 5.0-14.4^{0}C (Spence et al. 1996)

Rearing: 11.7^{0}C (Coutant 1977; Ferguson 1958; Huntsman 1942)
10.0-12.8^{0}C (Bell 1986)

IV. Fall Chinook Salmon:

Adult migration: 10.6-19.4^{0}C (Bell 1986, Spence et al. 1996)

Spawning: 10-12.8^{0}C (Bell 1986)
10-16.7^{0}C (Olson and Foster 1955)
5.6-13.9^{0}C (Spence et al. 1996)

Incubation: 10-12.8^{0}C (Bell 1986)
10-16.7^{0}C (Olson and Foster 1955)
10-12^{0}C (Heming 1982, Neitzel and Becker 1985, Garling and Masterson 1985)
5-14.4^{0}C (Spence et al. 1996)
> 12^{0}C alevins substantial reduction in survival (Ringler and Hall 1975)
> 15.6^{0}C mortality (Smith et al.1983)

Rearing: 12-14^{0}C (Bell 1986)

Smoltification: 4.5-15.5^{0}C typical migration (Spence et al. 1996)
ATPase Activity - 8^{0}C and 13^{0}C allow increased activity over a 6 week period, at 18^{0}C ATPase activity decreases over the same time period - inhibitory effect of water temperature on gill Na-K ATPase activity (Sauter unpublished data)

V. Chinook Salmon (general): Final Temperature Preferendum

Adult: 17.3^{0}C (Coutant 1977)

Yearling: 11.7^{0}C (Ferguson 1958, Huntsman 1942)

Spawning: 5.6-13.9^{0}C (Bjornn and Reiser, 1991)
5.6-10.6^{0}C (Bell 1986)
5.6-12.8^{0}C (Temperature Subcommittee, DEQ 1995)
15.5^{0}C causes spawning inhibition

Incubation: 5-14.4^{0}C (Bjornn and Reiser 1991)
13^{0}C (Bell 1986)
> 12.5^{0}C increases egg mortality and inhibits alevin development - produces only 50 % egg survival (California Department Water Resources 1988)

Rearing: 10-15.6^{0}C maximum productivity (Brett 1952)
12-14^{0}C preferred range (Brett 1952)
7.3^{0}C-14.6^{0}C preferred range (Beschta et al. 1987)
12.2^{0}C optimum (Beschta et al. 1987)
> 12.8^{0}C first feeding fry do not develop normally
> 15.5^{0}C disease increases mortality (Temperature Subcommittee, DEQ 1995)

Smoltification: < 12.2^{0}C for all salmonids (California Department Water Resources 1988)
18-21^{0}C sub-lethal and lethal loading stress (Brett 1952)

Independent Scientific Group (1996): Chinook salmon and other salmon species are not markedly different in their requirements.

Adult migration and spawning: optimum 10^{0}C, with range about 8 to 13^{0}C; stressful >15.6^{0}C; lethal 21^{0}C

Incubation: optimum <10^{0}C with range about 8 to 12^{0}C; stressful >13.3^{0}C; lethal >15.6^{0}C

Juvenile rearing: optimum 15^{0}C with range about 12 to 17^{0}C; stressful >18.3^{0}C; lethal 25^{0}C

National Marine Fisheries Service (1996):

Chinook habitat assessment: 10 to13.9^{0}C for properly functioning; 14 to15.5^{0}C at risk for spawning; and 14 to17.5^{0}C at risk for rearing and migration.

VI. Steelhead Trout:

Adult migration:	10-13^{0}C general preferred (Bjornn and Reiser 1991) 21^{0}C migration inhibition (Beschta et al. 1987)
Upper incipient lethal temperature:	21-22^{0}C (Hicks 1998)
Spawning:	3.9-9.4^0 C (Bell 1986, Spence et al. 1996) 4.4-12.8^{0}C (Swift 1976) Rainbow trout brood fish must be held at water temperatures below 13.3^{0}C and preferably not above 12.2^{0}C for a period of 2 to 6 months before spawning to produce eggs of good quality (Smith et al. 1983)
Incubation:	5.6-11.1^{0}C (Hicks 1998)

Preferred Temperatures Rearing:

summer run	10-12.8^{0}C (Bell 1986)
winter run	10-12.8^{0}C (Bell 1986)
fall run	10-14.4^{0}C (Bell 1986)
spring run	10-12.8^{0}C (Bell 1986) 7.3-14.6^{0}C preferred (Beschta et al. 1987) 10^{0}C optimum (Beschta et al. 1987)
Smoltification:	11-12.2^{0}C from 7.2^{0}C resulted in cessation of downstream movement (Hicks 1998) <12^{0}C (Hicks 1998)

VII. Coho Salmon:

Adult migration:	7.2-15.6^{0}C (Reiser and Bjornn 1979, Brett 1952)
Spawning:	4.4-9.4^{0}C (Reiser and Bjornn 1979, Brett 1952)

10-12.8^{0}C (Bell 1986)
7.2-12.8^{0}C (Hicks 1998)

Incubation:
4.4-13.3^{0}C (Reiser and Bjornn 1979, Brett 1952)
10-12.8^{0}C (Bell 1986)
8-9^{0}C (Sakh 1984)
4-6.5^{0}C (Dong 1981)
Egg mortality approx. 14^{0}C (Reiser and Bjornn 1979, Brett 1952)
>12^{0}C increased mortality (Allen 1957 in Murray and McPhail 1988)

Incubation (cont.):
>11^{0}C increased mortality (Murray and McPhail 1988)
1.3-10.9^{0}C produced best survival rates of eggs and alevins (Tang et al. 1987)
2-8^{0}C optimum range (Tang et al. 1987)

Lower lethal:
0.6-1.3^{0}C (Dong 1981)

Upper lethal:
12.5-14.5^{0}C (Dong 1981), University of Washington
10.9-12.5^{0}C (Dong 1981), Dungeness River, WA

Rearing:
11.8-14.6^{0}C (Reiser and Bjornn 1979, Brett 1952)
11.4^{0}C (Coutant 1977)
12-14^{0}C (Bell 1986)
Cessation of growth >20.3^{0}C (Temperature Subcommittee, DEQ 1995, Reiser and Bjornn 1979, Brett 1952)
11.8-14.6^{0}C, preferred (Beschta et al. 1987)
25.8^{0}C, upper lethal (Beschta et al. 1987)

Smoltification:
12-15.5^{0}C (Brett et al. 1958)
2.5-13.3^{0}C observed migration, most fish migrate before temperatures reach 11-12^{0}C (Spence et al. 1996)

Optimum Cruising Speed:
20^{0}C Under yearling and yearling approach velocities above dams exceeding 1.0 foot/second creates a problem in safeguarding under yearlings. Capacity to stem such a current for greater than one hour is limited to 18.5-21.5^{0}C (Brett et al. 1958)

Final Temperature Preferendum:

Adult:
11.4^{0}C (Coutant 1977) Laboratory
16.6^{0}C (Coutant 1977) L. Michigan

Upper lethal:
26^{0}C, incipient lethal temperature (Brett 1952)
Acclimation was 20^{0}C, 50 % mortality in 1,000 min.
25^{0}C (Temperature Subcommittee, DEQ 1995)

Preferred temperature:
12-14^{0}C, temperatures >15^{0}C were avoided (Brett 1952)

VIII. Chum salmon:

Adult migration:
8.3-15.6^{0}C (Bjornn and Reiser 1991)

Spawning: 7.2-12.8^{0}C (Bjornn and Reiser 1991)

Incubation: 8^{0}C (Beacham and Murray 1985)
4.4-13.3^{0}C (Bjornn and Reiser 1991)
6-10^{0}C, maximum efficiency for conversion of yolk to tissue (Beacham and Murray 1985)
12^{0}C, alevin mortality occurred 1-3 days after hatch (Beacham and Murray 1985)

Rearing: 14.1^{0}C (Coutant 1977, Ferguson 1958, Huntsman 1942)
10-12.8^{0}C (Bell 1986)
11.2-14.6^{0}C, preferred (Beschta et al. 1987)
12-14^{0}C, preferred (Brett 1952)
13.5^{0}C, optimum (Beschta et al. 1987)
25.8^{0}C, upper lethal (Beschta et al. 1987)

Final temperature preferendum:

Under yearling: 14.1^{0}C (Coutant 1977) Laboratory

Yearling: 14.1^{0}C (Ferguson 1958) Laboratory
14.1^{0}C (Huntsman 1942) Laboratory

Smoltification: Information not available

Upper lethal: 25.4^{0}C, incipient lethal temperature (Brett 1952)
Acclimation was 20^{0}C, 50 % mortality in 1,000 min.

IX. Cutthroat trout:

Adult migration: Information not available
18-22.8^{0}C upper lethal temperature range (Kruzic 1998)

Adult Holding: Smith et al. (1983), west-slope cutthroat trout: Females held in fluctuating temperatures (2-10^{0}C) had significantly better eggs than those held at a constant 10^{0}C. Elevated temperatures experienced by mature females affected subsequent viability and survival of embryos.

Spawning: 6.1-17.2^{0}C (Beschta et al.1987, Bell 1986)

Incubation: Information not available

Rearing: 10^{0}C (Bell 1986)
9.5-12.9^{0}C, preferred (Beschta et al. 1987)
23^{0}C, upper lethal (Beschta et al. 1987)
22.8^{0}C, upper lethal (Bell 1986)

Smoltification: Information not available

X. Bull trout:

Migration: 10-12^{0}C (EPA 1997, DEQ 1995)

Spawning:	<9-10^{0}C, initiate spawning, MT (Temperature Subcommittee, DEQ 1995) <9^{0}C, initiate spawning, B.C. (Spence et al. 1996, Temperature Subcommittee, DEQ 1995, Pratt 1992) 4.5^{0}C, Metolius River, Oregon (Spence et al. 1996, Temperature Subcommittee, DEQ 1995) 4-10^{0}C (Temperature Subcommittee, DEQ 1995) 5-6.5^{0}C, peak spawning activities (EPA 1997)
Incubation:	8-10^{0}C, 0-20 % survived to hatch, B.C. (Temperature Subcommittee, DEQ 1995) 6^{0}C, 60-90 % survived to hatch, B.C. (Temperature Subcommittee, DEQ 1995) 2-4^{0}C, 80-95 % survived to hatch, B.C. (Temperature Subcommittee, DEQ 1995) 4-6^{0}C, MT (Temperature Subcommittee, DEQ 1995) 1-6^{0}C (Temperature Subcommittee, DEQ 1995) 2-6^{0}C (Spence et al. 1996)
Rearing:	4^{0}C optimal temperature for growth, B.C. (Temperature Subcommittee, DEQ 1995) 4.5^{0}C, Metolius River, Oregon (Temperature Subcommittee, DEQ 1995) 4-4.5^{0}C, optimum fry growth (Temperature Subcommittee, DEQ 1995) 4-10^{0}C, optimum juvenile growth (Temperature Subcommittee, DEQ 1995) <10^{0}C, Metolius River (EPA 1997) >14^{0}C is a thermal barrier in closely related arctic char (Pratt 1992)
Adult resident:	19^{0}C, no bull trout were observed, MT (Temperature Subcommittee, DEQ 1995) 15-18^{0}C, bull trout were present, MT (Temperature Subcommittee, DEQ 1995) <16^{0}C, bull trout present, John Day Basin, OR (Temperature Subcommittee, DEQ 1995) <12^{0}C, highest densities of bull trout, MT (Temperature Subcommittee, DEQ 1995) 9-13^{0}C, adult preference (Temperature Subcommittee, DEQ 1995) Less than or equal to 12^{0}C, highest adult density (Temperature Subcommittee, DEQ 1995) 4-18^{0}C, adults present (Temperature Subcommittee, DEQ 1995) <15^{0}C vertical distribution in lakes (Pratt 1992)
Competition:	12^{0}C, Metolius River, reach susceptible to brook trout invasion (EPA 1997)

Appendix A References

Bell, M. 1986. Fisheries Handbook. Chapter 11.

Beacham, T.D. and C.B. Murray. 1985. Effect of female size, egg size, and water temperature on developmental biology of chum salmon (*Oncorhynchus keta*) from the Nitinat River, British Columbia. Can. J. Fish. Aquat. Sci. 42:1755-1765.

Berman, C.H. 1990. Effect of elevated holding temperatures on adult spring chinook salmon reproductive success. MS Thesis. University of Washington, Seattle.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, T.D. Hofstra. 1987. Stream Temperature and aquatic habitat: fisheries and forestry interactions, pp. 191-232. *In* E.O. Salo and T.W. Cundy (editors) Streamside Management: Forestry and Fishery Interactions, Institute of Forest Resources, University of Washington. Contribution No. 57.

Bjornn, T.C. and D.W. Reiser. 1991. Habitat requirements of salmonids in streams. In: Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Spec. Pub. 19:83-138.

Bouck, G.R., G.A. Chapman, P.W. Schneider, and D.G. Stevens. 1975. Effects of holding temperatures on reproductive development in adult sockeye salmon (*Oncorhynchus nerka*). In: 26th Annual Northwest Fish Culture Conference. Editor J.R. Donaldson. pp.24-40.

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, Genus *Oncorhynchus*. J. Fish. Res. Bd. Can. 9:265-323.

Brett, J. R., M. Hollands, and D.F. Alderdice. 1958. The effect of temperature on the cruising speed of young sockeye and coho salmon. J. Fish. Res. Bd. Can. 32: 485-491.

Burgner, R.L. 1991. Life history of sockeye salmon, pp 3-117. *In* C. Groot and L. Margolis (editors) Pacific Salmon Life Histories.

California Department of Water Resources. 1988. Water temperature effects on chinook salmon (*Oncorhynchus tshawytscha*) with emphasis on the Sacramento River: A literature review. Northern District Office Report. Red Bluff, CA 42 pp.

Combs, B. D. 1965. Effect of temperature on the development of salmon eggs. Prog. Fish-Cult. 27: 134-137.

Coutant, C.C. 1977. Compilation of temperature preference data. J. Fish. Res. Bd. Can. 34:739-745.

Coutant, C.C. 1999. Perspectives on temperature in the Pacific Northwest's fresh waters. Oak Ridge National Laboratory, Environ. Sci. div. Pub. No. 4849 108 pp.

Department of Fisheries of Canada and the International Pacific Salmon Fisheries Commission. 1952. Report on the fisheries problem created by the development of power in the Nechako-Kemano-Nanika river systems, Supplement #1, Temperature changes in the Nechako River and their effects on the salmon population. 42 pp.

Dong, J.N. 1981. Thermal tolerance and rate of development of coho salmon embryos. Master's thesis. University of Washington.

EPA. 1997. Administrative record, water quality standards for Idaho; final rule (see specific temperature criteria for bull trout in Idaho Streams: technical basis, notes, and issues). 40 CFR Part 131, July 31, 1997.

Ferguson, R.G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Can. 15:607-624.

Garling, D.L. and M. Masterson. 1985. Survival of Lake Michigan chinook salmon eggs and fry incubated at three temperatures. Prog. Fish-Cult. 47:63-66.

Heming, T. A. 1982. Effects of temperature on utilization of yolk by chinook salmon (*Oncorhynchus tshawytscha*) eggs and alevins. Can. J. Fish. Aquat. Sci. 39:184-190.

Hicks, M. 1998. Preliminary review draft discussion paper: Supplementary appendix: Evaluating standards for protecting aquatic life in Washington's surface water quality standards. Washington Department of Ecology, Water Quality Program.

Huntsman, A.G. 1942. Death of salmon and trout with high temperatures. J. Fish. Res. Bd. Can. 5:485-501.

Independent Scientific Group. 1996. Return to the river: restoration of salmonid fishes in the Columbia River ecosystem.

Kruzic, L.M. 1998. Ecology of juvenile coho salmon within the upper South Umpqua River basin, Oregon. MS Thesis. University of Idaho.

Major, R.L. and J.L. Mighell. 1966. Influence of Rocky Reach Dam and the temperature of the Okanogan River on the upstream migration of sockeye salmon. U.S. Fish and Wildlife Service Fishery Bulletin 66: 131-147.

Marine, K. R. 1992. A background investigation and review of the effects of elevated water temperature on reproductive performance of adult chinook salmon. Department of Wildlife and Fisheries Biology, University of California, Davis.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to chinook salmon. Prepare for U.S. EPA Region 10, Seattle, WA 279 pp.

Murray, C.B. and J.D. McPhail. 1988. Effect of incubation temperature on the development of five species of Pacific salmon (*Oncorhynchus*) embryos and alevins. Can. J. Zool. 66:266-273.

National Marine Fisheries Service. 1996. Making ESA determinations of effect for individual or grouped actions at the watershed scale. NW Regional Office, Portland, OR.

Neitzel, D.A. and C.D. Becker. 1985. Tolerance of eggs, embryos, and alevins of chinook salmon to temperature changes and reduced humidity in dewatered redds. Trans. Am. Fish. Soc. 114:267-273.

Olson, P.A. and R.F. Foster. 1955. Temperature tolerance of eggs and young of Columbia River chinook salmon. Trans. Am. Fish. Soc. 85:203-207.

Pratt, K.L. 1992. A review of bull trout life history. Proceedings of the Gearhart Mountain Bull Trout Workshop, Oregon Chapter of the American Fisheries Society.

Reiser, D.W. and T.C. Bjornn. 1979. Habitat requirements of anadromous salmonids. Gen. Tech. Rep. PNW-96. USDA Forest Service, Pacific NW Forest and Range Exper. Station. Portland, OR 54 pp.

Ringler, N.H. and J.D. Hall. 1975. Effects of logging on water temperature and dissolved oxygen in spawning beds. Trans. Am. Fish. Soc. 104:111-121.

Sakh. 1984. Egg incubation in coho salmon as a function of water temperature. Rybn. Khoz. 10:21-22.

Sauter, S. Unpublished data. Columbia River Research Laboratory, Biological Resources Division, USGS.

Smith, C.E, W.P. Dwyer, and R.G. Piper. 1983. Effect of water temperature on egg quality of cutthroat trout. Prog. Fish Cult. 45:176-178.

Spence, B.C, G.A. Lomnicky, R.M. Hughes, R.P. Novitzki. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057. ManTech Environmental Research Services Corp., Corvallis, OR.

Swift, C.H. III. 1976. Estimation of stream discharges preferred by steelhead trout for spawning and rearing in western Washington. 50 pp.

Tang, J., M.D. Bryant, and E.L. Brannon. 1987. Effect of temperature extremes on the mortality and development rates of coho salmon embryos and alevins. Prog. Fish Cult. 49:167-174.

Temperature Subcommittee, Technical Advisory and Policy Advisory Committees. 1995. Temperature 1992-1994 Water Quality Standard Review, Final Issue Paper. Oregon Department of Environmental Quality.

Appendix B

Source Code Tests

The source code for the numerical solution to Equation (2), incorporating reverse particle tracking, was tested against a number of benchmark cases for which the solution was exactly known. In addition, the simulations for these benchmark cases using reverse particle tracking were compared with simulations using the numerical schemes from two widely-applied water quality modeling packages, Water Quality for River-Reservoir Systems (WQRRS) (Smith, 1978) and QUAL2E (Brown and Barnwell, 1987).

NUMERICAL METHODS

Reverse Particle Tracking

Reverse particle tracking, the numerical method used in this study, is a mixed Eulerian-Lagrangian scheme. As described by Zhang et al (1993), the state variable is simulated in the advection step by sending a fictitious particle from each node, j (Figure 5), backward to the point,

$$x_j' = x_j - \int_{t_k}^{t_{k=1}} u^* \, dt \qquad \text{(B.1)}$$

where,

u^* = velocity encountered by the particle while moving from x'_j to x_j.

WQRRS

The numerical method used in WQRRS is a finite difference Eulerian scheme that begins with the mass balance equation for a state variable, T, stated in matrix form as

$$[V]\left\{\dot{T}\right\} = [S]\{T\} + \{P\} \qquad \text{(B.2)}$$

where,

$[V]$ = matrix with element volumes on the diagonal and zeroes elsewhere,

$\left\{\dot{T}\right\}$ = vector of the rates of change of T in each element,

$[S]$ = Matrix of coefficients multiplies the state variable, T,

$\{T\}$ = Vector of the state variable in each segment,

$[P]$ = Vector of constant terms for each segment.

Equation (B.2) is solved numerically by assuming

$$T_{t+\Delta t} = T_t + \frac{\Delta t}{2}(\dot{T}_t + \dot{T}_{t+\Delta t}) \tag{B.3}$$

This leads to the following solution

$$\left[S^*\right]\left\{\dot{T}\right\} = \left\{P^*\right\} \tag{B.4}$$

where,

$$\left[S^*\right] = [V] - \frac{\Delta t}{2}[S]$$

$$\left\{P^*\right\} = [S]\{B\} + \{P\}$$

$$B = T_t + \frac{\Delta t}{2}\dot{T}_t$$

QUAL2E

QUAL2E (Brown and Barnwell, 1987) uses an upstream, implicit method to solve the finite difference equation for a state variable, T

$$\frac{T_j^{k+1} - T_j^k}{\Delta t} = -\frac{Q_j\, T_j^{k+1} - Q_{j-1}\, T_{j-1}^{k+1}}{V_j} + r_j\, T_j^{k+1} + P_j \tag{B.5}$$

where,

Q_j = flow out of the j^{th} element,

V_j = volume of the j^{th} element,

r_j = first order rate constant,

P_j = internal sources in the j^{th} element.

Equation (B.5) does not include a term for longitudinal dispersion, as does the more general form of the equation found in the QUAL2E documentation (Brown and Barnwell, 1987).

TEST CASES

Test Case A

Test Case A is based on an idealized river system 100 miles long divided into 100 equal segments. The longitudinal speed of the water is one mile/day. The boundary condition at x=0 for the state variable, T, is kept constant at 20 units and decays according to a first-order loss rate, K = 0.20. In a Lagrangian frame of reference,

$$\frac{dT}{dt} = -K\,T \tag{B.6}$$

and in an Eulerian frame of reference

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = -K\,T \tag{B.7}$$

where,

U = (constant) longitudinal speed of the water.

The solutions to Test Case A, obtained with reverse particle tracking, WQRRS and QUAL2E are shown in Figure B-1.

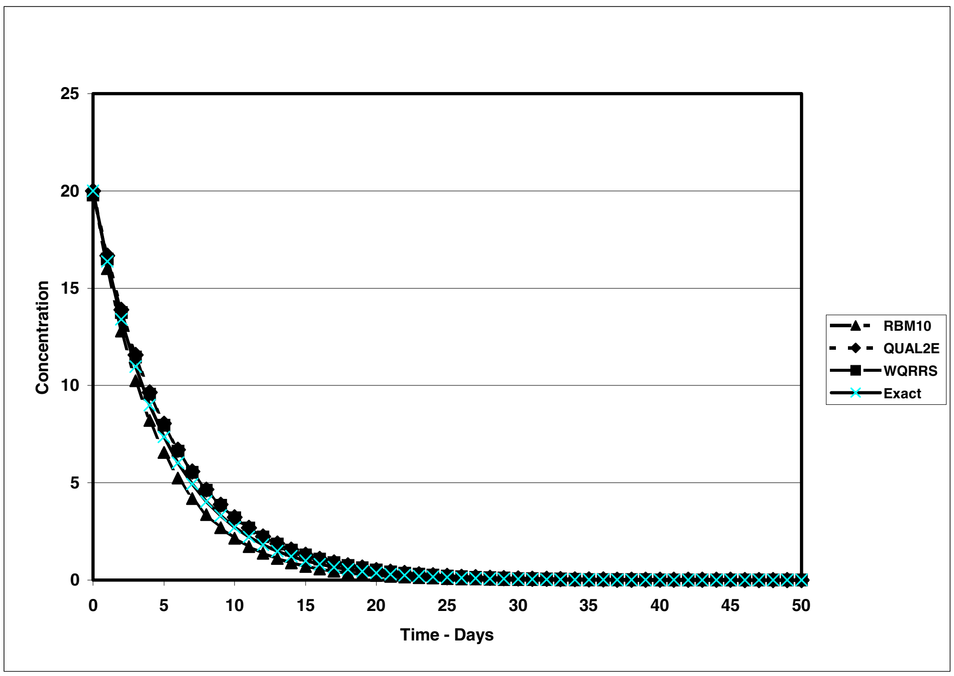

Figure B-1. Steady state flow and boundary condition - First order decay

Test Case B

The geometry and hydrology for this case are the same as for Test Case A above. The boundary for the state variable, T, is varied according to

$$T(x = 0) = 10 + 10\sin(2\pi t/P_0)$$

where,

P_0 = 10, 20, 50, 100 days

The results from the various numerical schemes are shown in Figures B-2 – B-5.

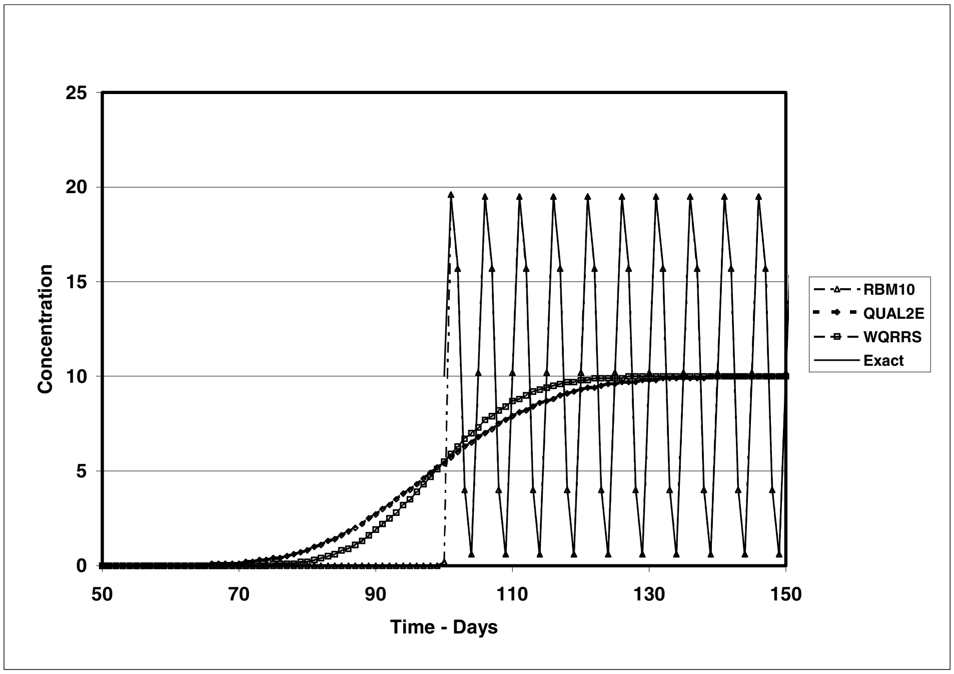

Figure B-2. Harmonic boundary condition with period = 10 days

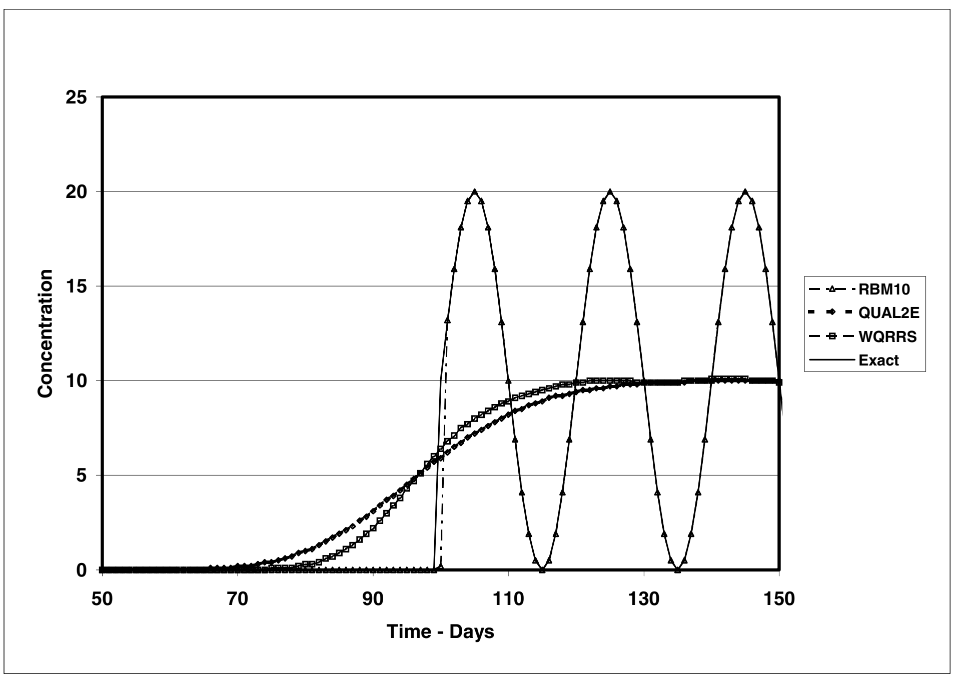

Figure B-3. Harmonic boundary condition with period = 20 days

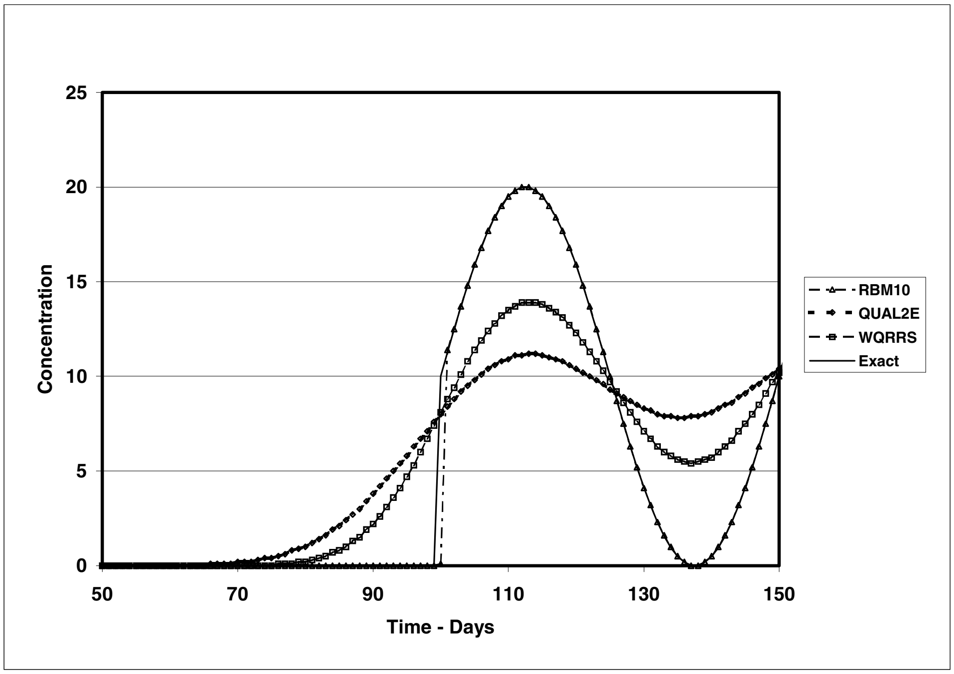

Figure B-4. Harmonic boundary condition with period = 50 days

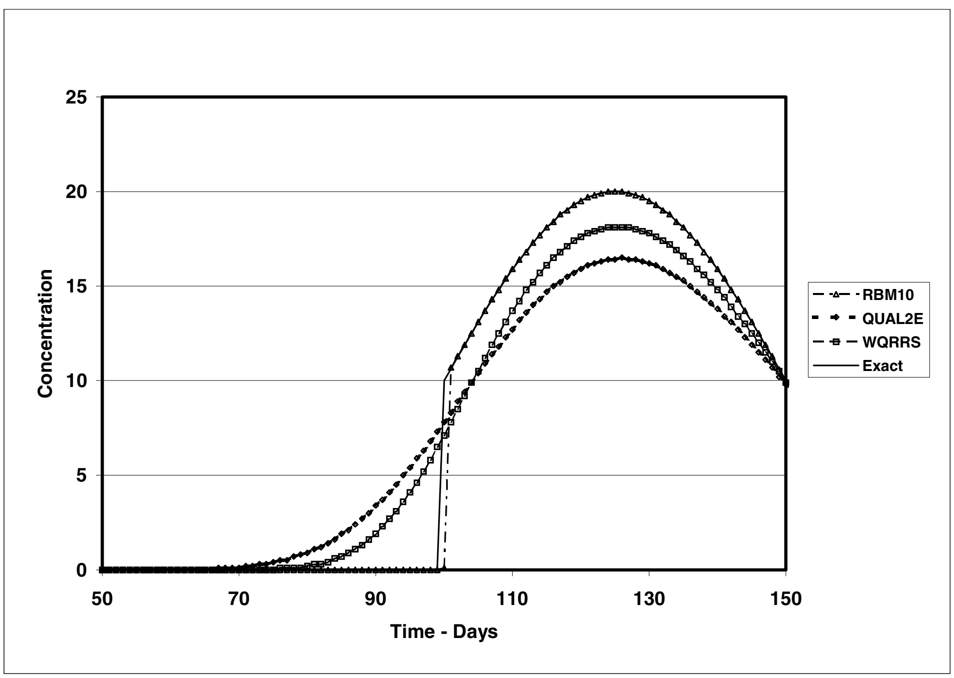

Figure B-5. Harmonic boundary condition with period = 100 days

Test Case C

Test Case C uses the same geometry and hydrology as the previous two test cases. The boundary condition at X = 0 is defined as

$$T(t,x=0) \quad = \quad 20\,u_{-1}(t)$$

Where,

$u_{-1}(t)$ = the generalized function such that $T(t,x=0) = 0$ for $t<0$,

$T(t,x=0) = 1$ for $t>0$.

Results of simulations are shown in Figure B-6.

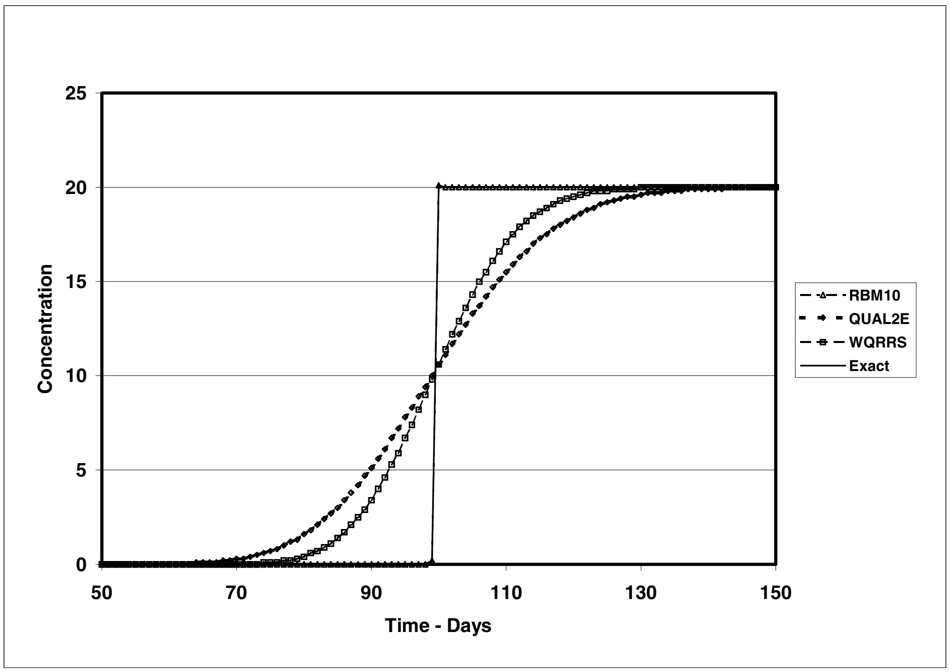

Figure B-6. Step function boundary condition

Test Case D

Test Case D is similar in all respects to Test Case B, with the exception that the segments used to describe the system are unequal and the periods associated with the harmonic functions describing the boundary conditions are

P_0 = 5, 10, 20, 50 days.

Segment 1 (the most upstream segment) is 0.5 miles in length, Segment 2 is 1.0 miles in length, Segment 3 is 1.5 miles in length, Segment 4 is 0.5 miles in length, Segment 5 is 1.0 miles in length, Segment 7 is 1.5 miles in length, the pattern repeating in this way for the entire length of the idealized system. The simulation results for this case are shown in Figures B-7 – B-10.

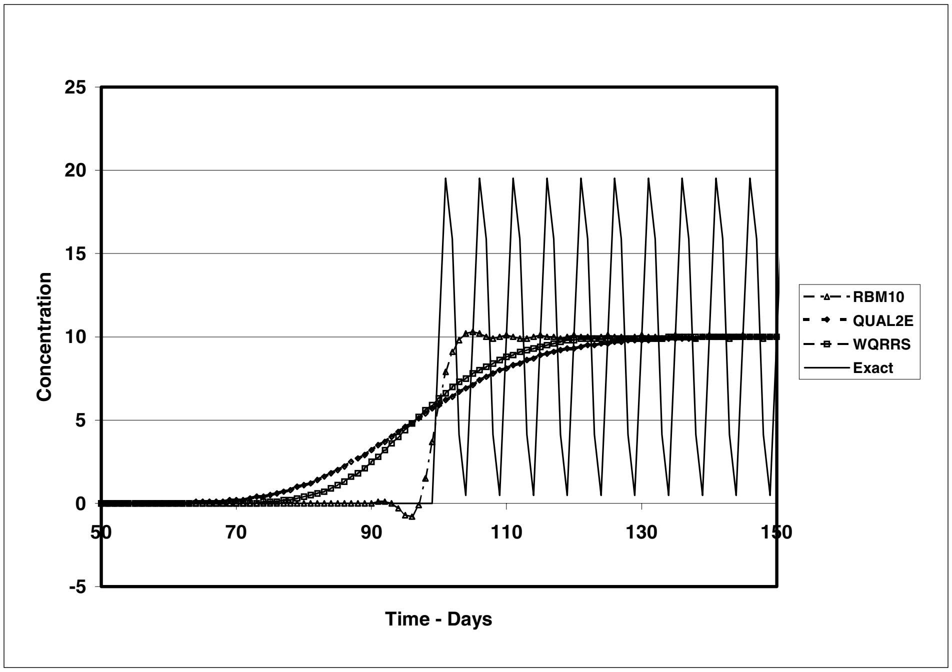

Figure B-7. Harmonic boundary condition with period = 5 days and unequal segment volumes

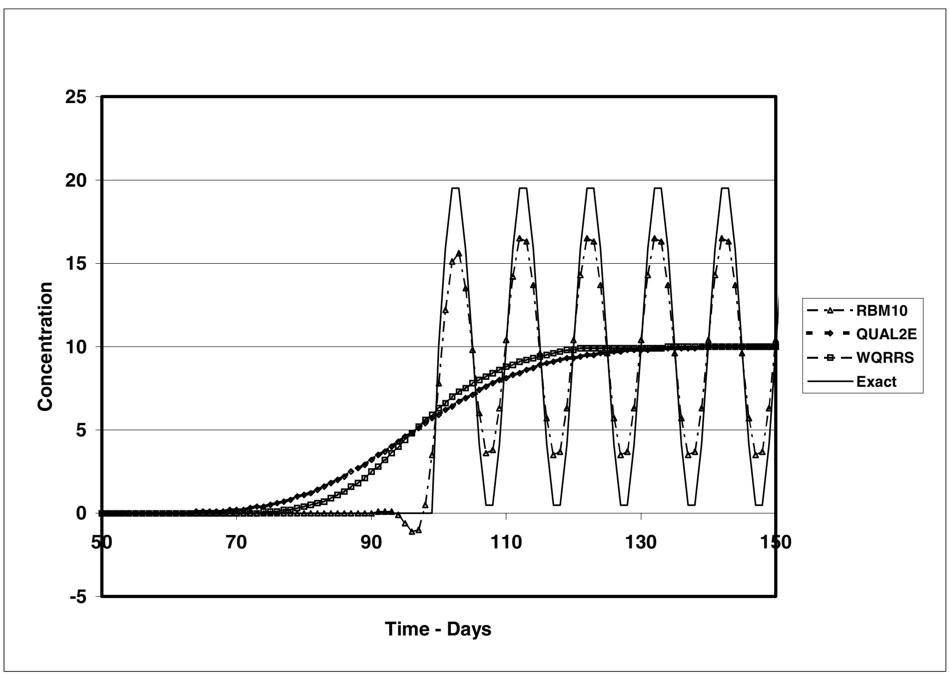

Figure B-8. Harmonic boundary condition with period = 10 days and unequal segment volumes

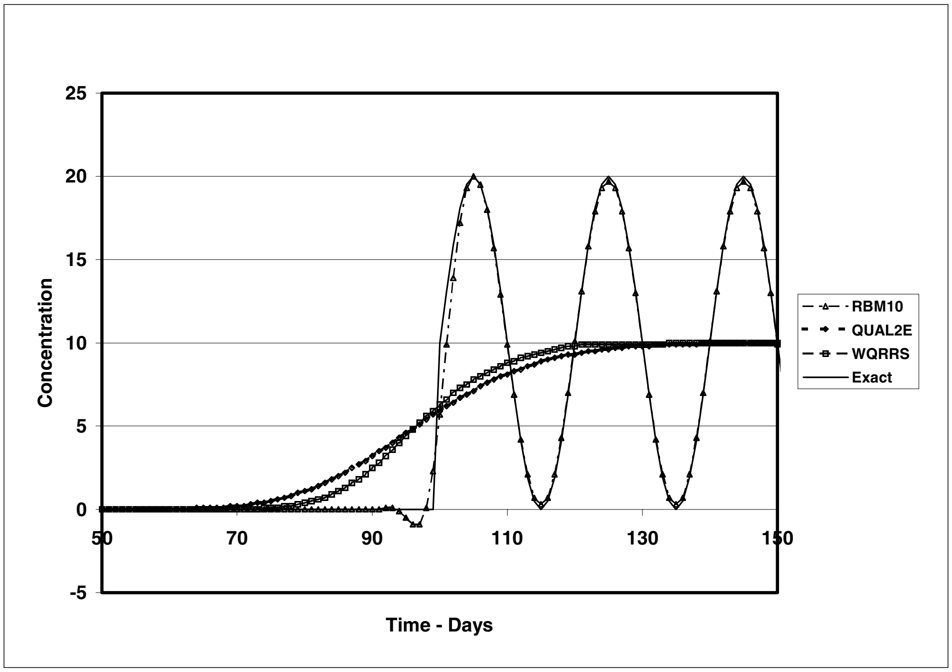

Figure B-9. Harmonic boundary condition with period = 20 days and unequal segment volumes

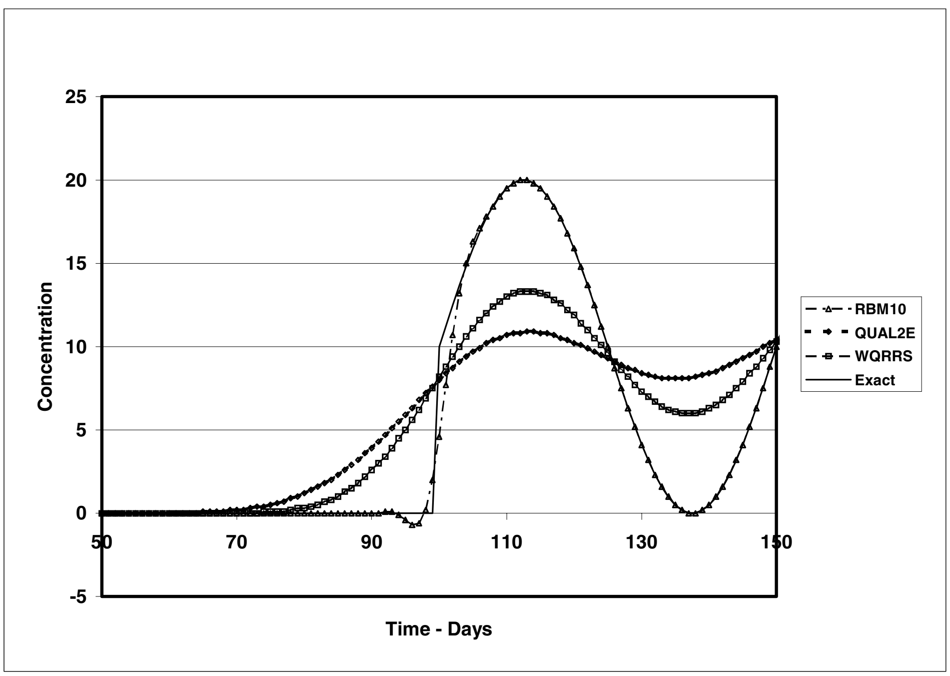

Figure B-10. Harmonic boundary condition with period = 50 days and unequal segment volumes

Test Case E

Test Case E is developed from solutions to the linearized form of the thermal energy budget equation (Edinger et al, 1974). In Lagrangian form,

$$\frac{dT}{dt} = K(T_{equil} - T) \qquad \text{(B.8)}$$

And in Eulerian form,

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = K(T_{equil} - T) \qquad \text{(B.9)}$$

where,

K = a first-order rate constant which is a function of meteorological parameters and water depth,

T_{equil} = water temperature at which there is no heat transfer across the the air-water interface,

= $T_{\Delta} \sin(2\,\Pi\, t/ P_{\Delta}) + T_{avg}$.

The Laplace transform gives the following solution

$$T(t) = T_0(t) + KT_{\Delta}\,[\frac{\cos(\omega(t-\tau))}{\omega^2 + K^2}(\omega\, e^{-K\tau} - \omega\cos(\omega\tau) + K\sin(\omega\tau))$$

$$+\frac{\sin(\omega(t-\tau))}{\omega^2 + K^2}(-K\, e^{-K\tau} + K\cos(\omega\tau) + \omega\sin(\omega\tau)] + T_{avg}\,(1 - e^{-K\tau}) \qquad \text{(B.10)}$$

where,

T_0 = boundary condition at x = 0

= $\Delta T_0 \sin(2\,\Pi\, t/ P_0) + T_{0\,avg}$,

ω = $2\,\Pi / P_{\Delta}$,

τ = x/U.

Simulations were done for specific cases in which

ΔT_0 = 10,

$T_{0\,avg}$ = 10,

T_{Δ} = 10,

T_{avg} = 15,

P_{Δ} = 360,

P_0 = 5, 10, 20, 50,

x/U = 5.

The results are shown in Figures B-11 – B-14.

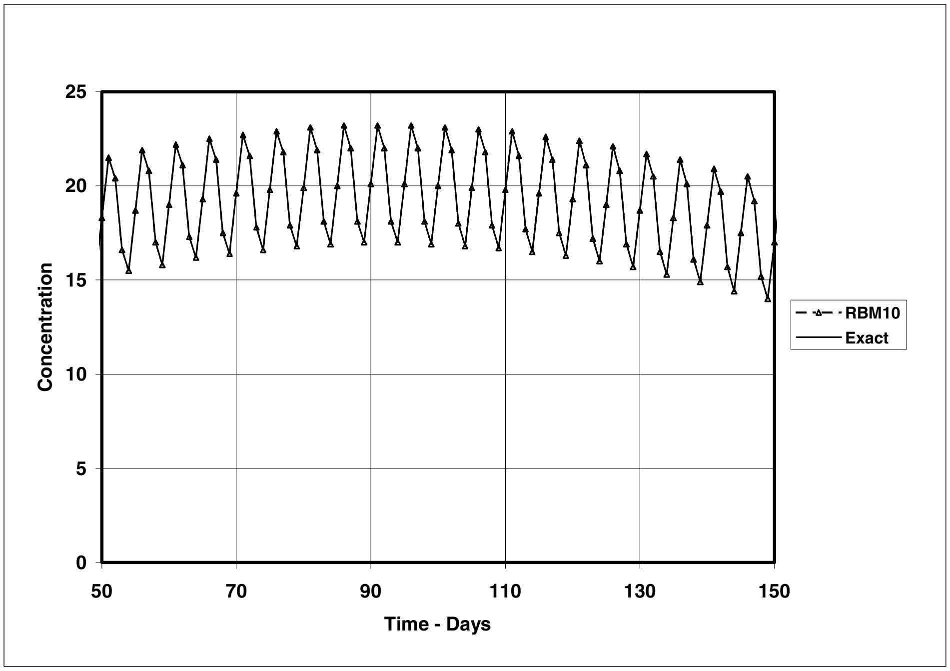

Figure B-11a. Harmonic boundary condition with period = 5 days and equal segment volumes. RBM10 compared to exact solution

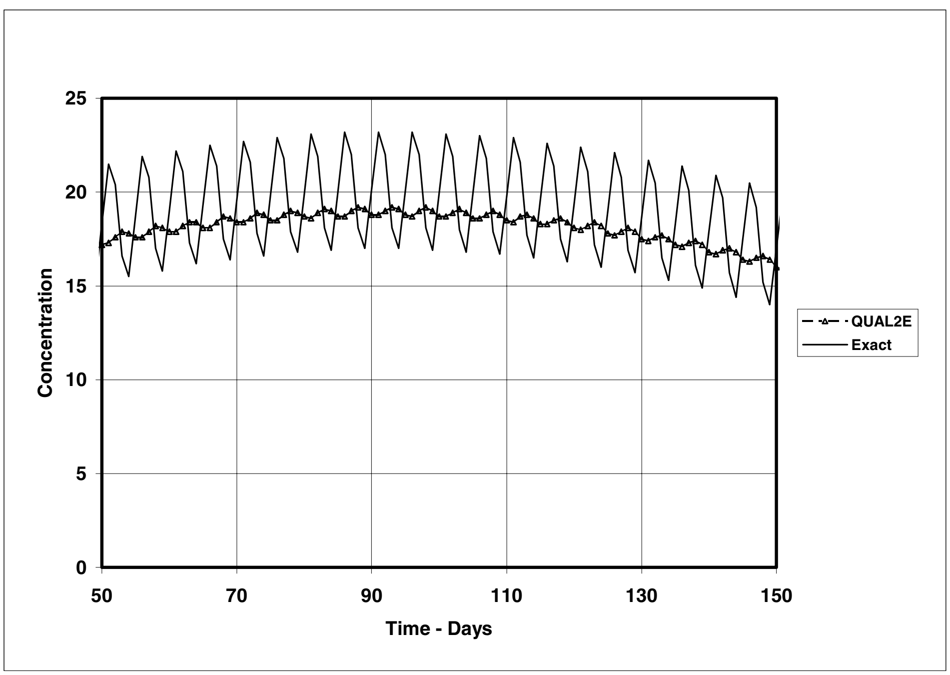

Figure B-11b. Harmonic boundary condition with period = 5 days and equal segment volumes. QUAL2E compared to exact solution

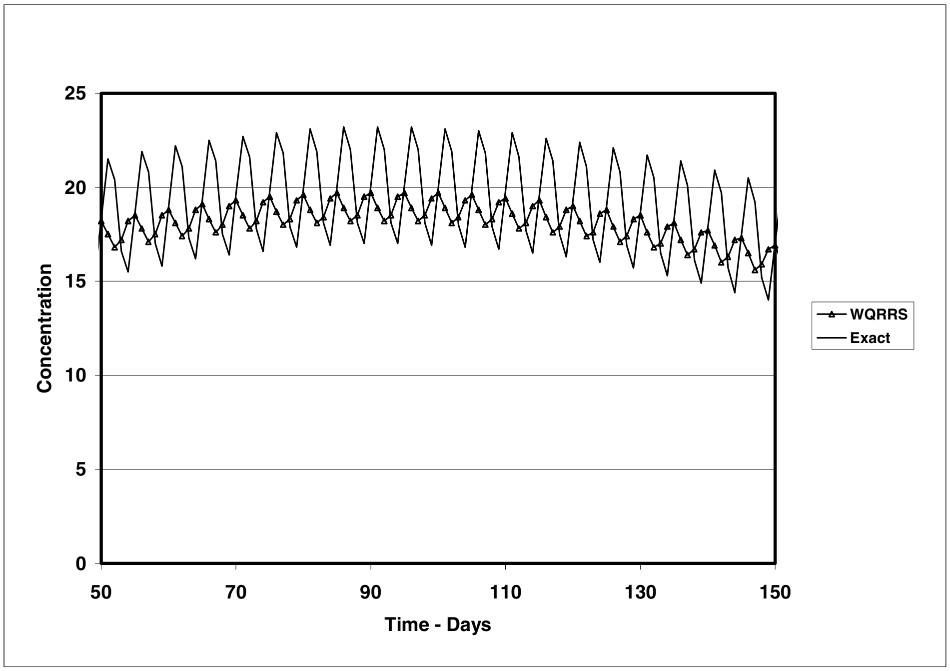

Figure B-11c. Harmonic boundary condition with period = 5 days and equal segment volumes. WQRRS compared to exact solution

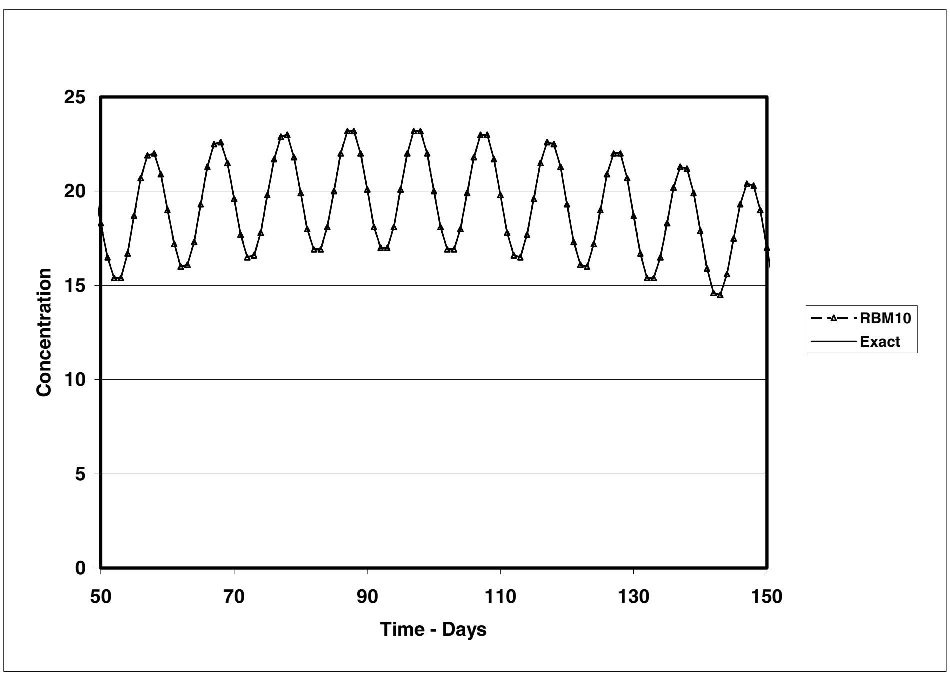

Figure B-12a. Harmonic boundary condition with period = 10 days and equal segment volumes. RBM10 compared to exact solution

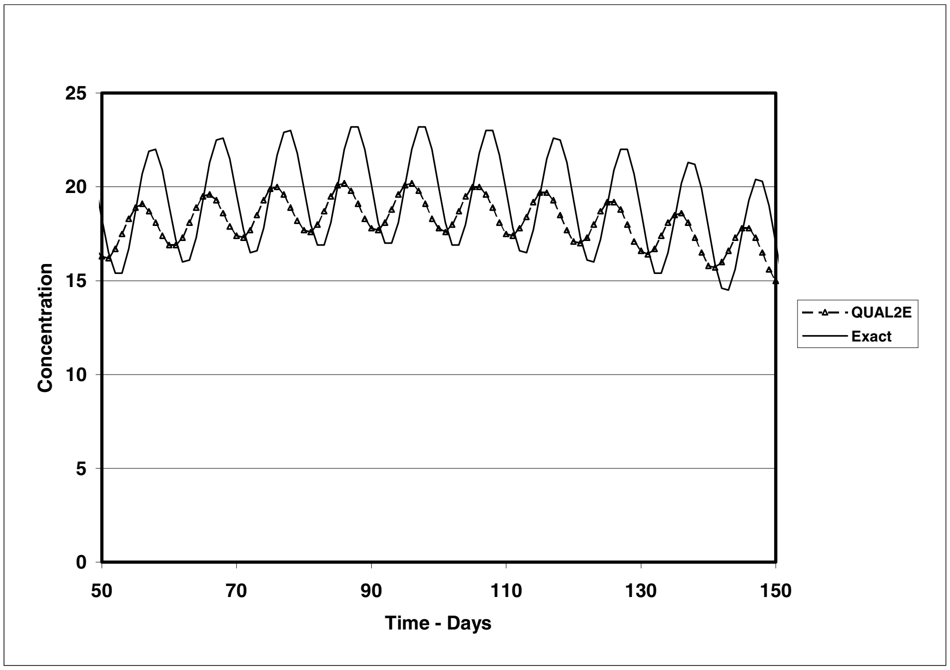

Figure B-12b. Harmonic boundary condition with period = 10 days and equal segment volumes. QUAL2E compared to exact solution

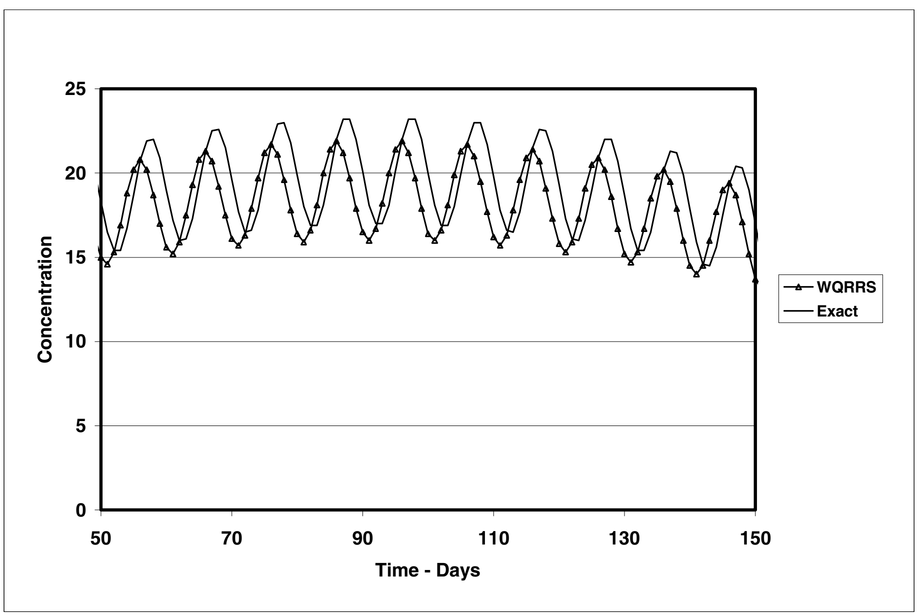

Figure B-12c. Harmonic boundary condition with period = 10 days and equal segment volumes. WQRRS compared to exact solution

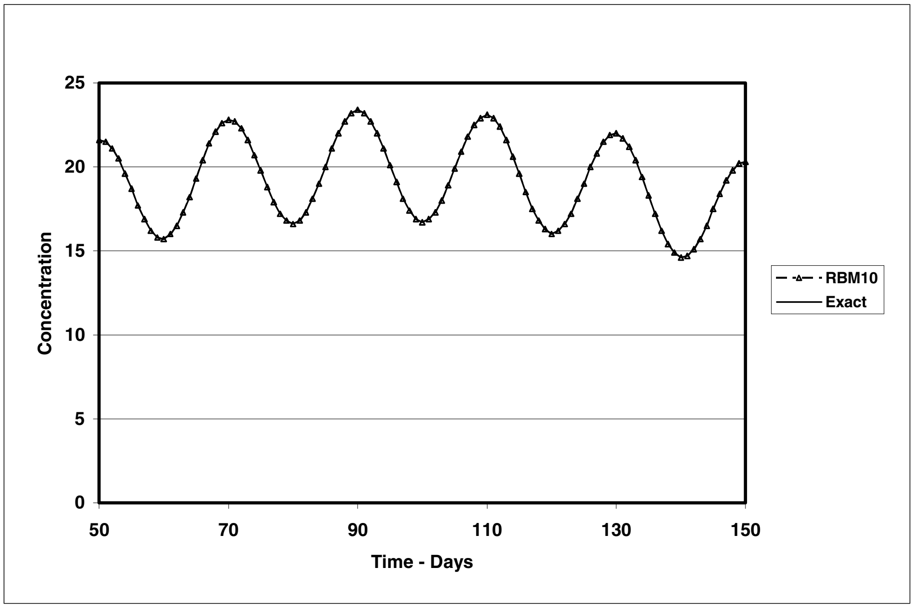

Figure B-13a. Harmonic boundary condition with period = 20 days and equal segment volumes. RBM10 compared to exact solution

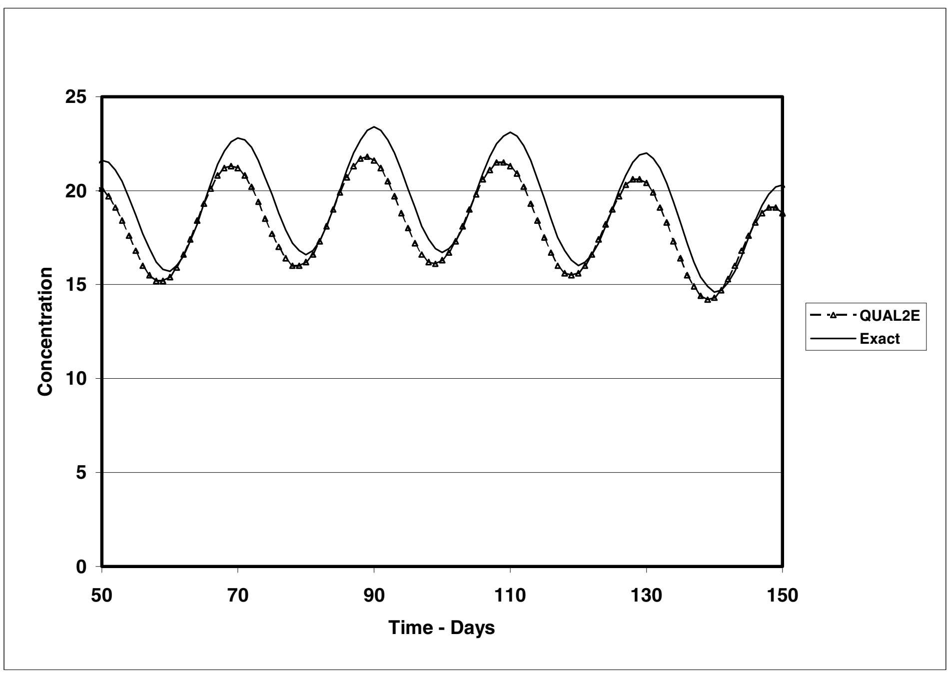

Figure B-13b. Harmonic boundary condition with period = 20 days and equal segment volumes. QUAL2E compared to exact solution

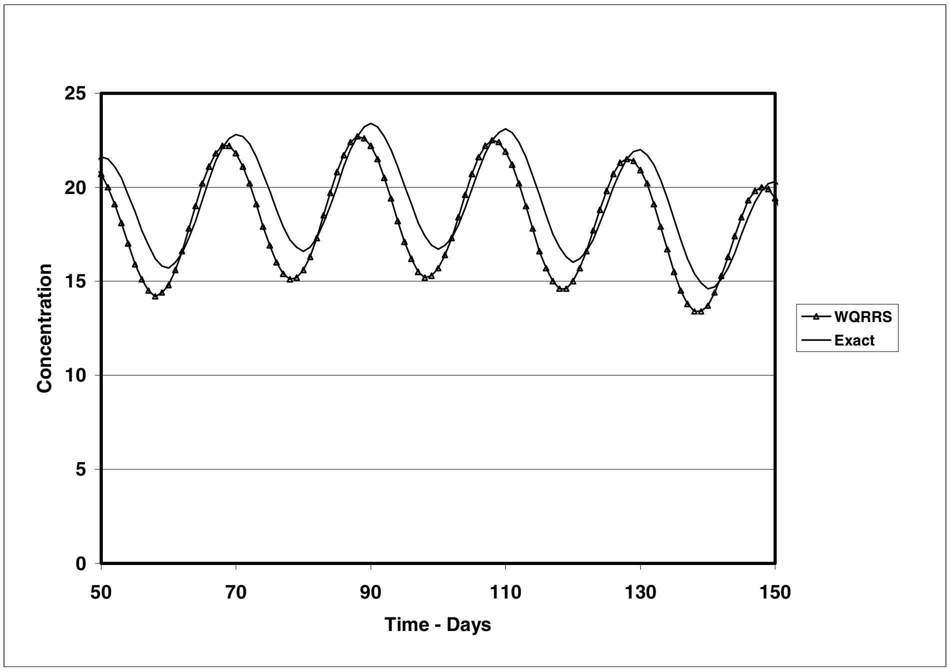

Figure B-13c. Harmonic boundary condition with period = 20 days and equal segment volumes. WQRRS compared to exact solution

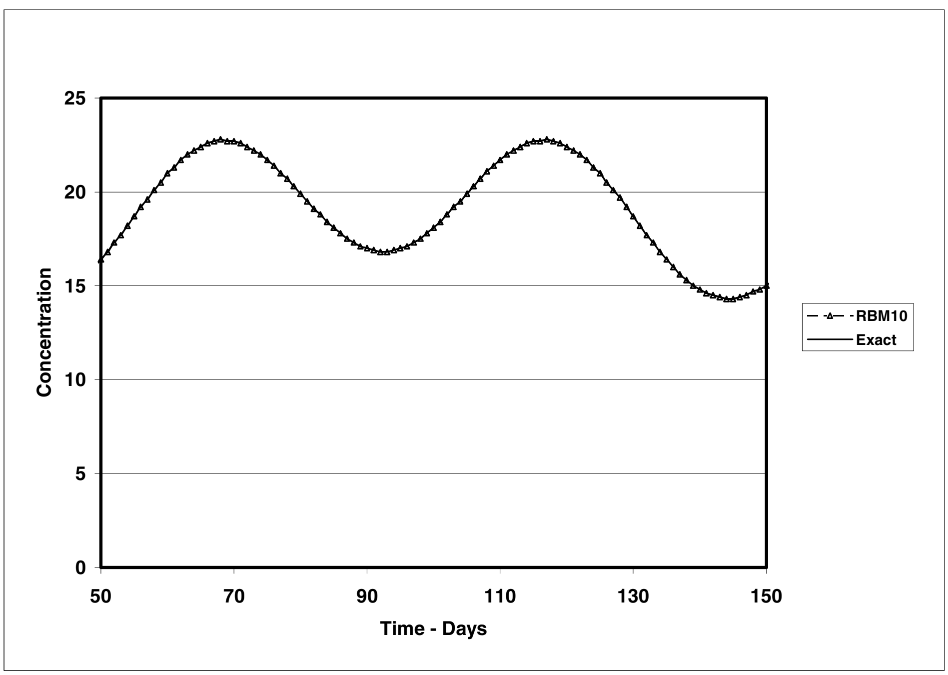

Figure B-14a. Harmonic boundary condition with period = 50 days and equal segment volumes. RBM10 compared to exact solution

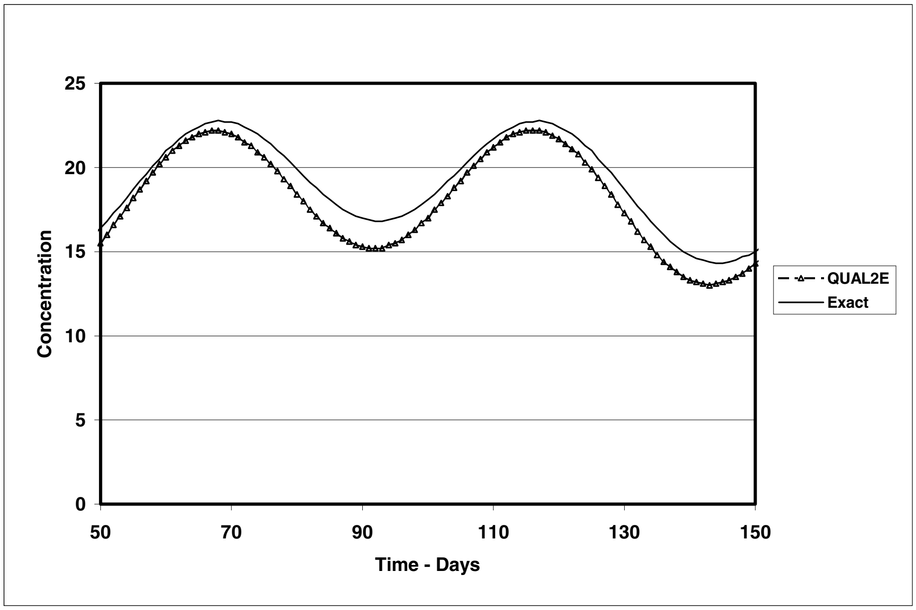

Figure B-14b. Harmonic boundary condition with period = 50 days and equal segment volumes. QUAL2E compared to exact solution

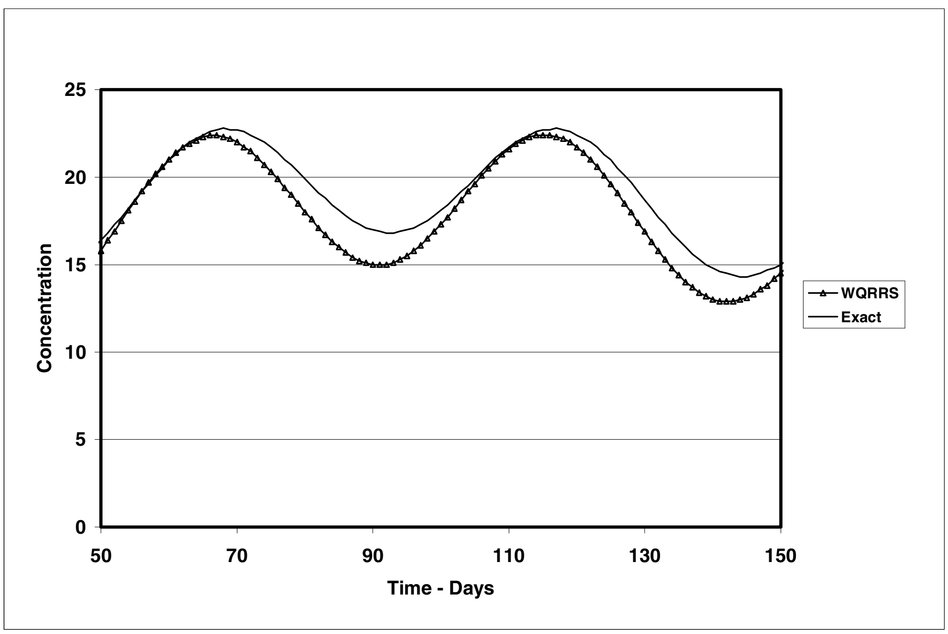

Figure B-14c. Harmonic boundary condition with period = 50 days and equal segment volumes. WQRRS compared to exact solution

DISCUSSION

For the Test Case A, the steady-state problem with a first-order decay constant, K (Figure B.1), all three methods differ slightly from the exact solution. This error is a function of the ratio of the integration time step to the time constant (1/K). Reducing this ratio will also reduce the errors in all simulations.

Test Cases B – E provide indications of model performance in propagating high frequencies when advection is important. The reverse particle tracking method gives nearly exact solutions when the Courant number, U $\Delta x/\Delta t$, is equal to one (Test Cases, B, C, and E). For the case when the Courant number is not always equal to one (Test Case D), reverse particle begins to show the effects of numerical dispersion when the period, $P_0 = 10$ or lower.

Numerical dispersion is evident in simulations using WQRRS and QUAL2E for all test conditions including those where the Courant number is equal to one. In Test Cases B, C and D, the effects of numerical dispersion on amplitudes are severe when the period, $P_0 = 20$ or lower. WQRRS has somewhat better high-frequency response than QUAL2E, however. Both amplitude and phase of QUAL2E and WQRRS simulations are affected in Test Case E.

Appendix C

GEOMETRIC AND HYDRAULIC PROPERTIES OF THE COLUMBIA AND SNAKE RIVERS FOR EXISTING CONDITIONS AND FOR UNIMPOUNDED CONDITIONS

Table C-1. Surface elevation, volume and surface area of run-of-the-river reservoir segments in the Snake River from Lewiston, Idaho to Ice Harbor Dam.

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	Volume (acre-feet)	Area (acres)
140.0	137.3	746	20825.0	597
137.3	134.6	746	20825.0	597
134.6	131.9	746	20825.0	597
131.9	129.2	746	20825.0	597
129.2	126.5	746	20825.0	597
126.5	123.8	746	35044.0	558
123.8	121.1	746	35044.0	558
121.1	118.4	746	35044.0	558
118.4	116.3	746	38586.0	524
116.3	114.3	746	38586.0	524
114.3	112.3	746	38586.0	524
112.3	110.1	746	57027.0	718
110.1	107.9	746	57027.0	718
107.9	104.5	646	20883.2	580
104.5	101.0	646	20883.2	580
101.0	97.6	646	20883.2	580
97.6	94.1	646	20883.2	580
94.1	90.7	646	20883.2	580
90.7	87.4	646	50635.0	905
87.4	84.0	646	50635.0	905
84.0	81.5	646	56622.0	814
81.5	78.9	646	56622.0	814
78.9	76.6	646	55658.0	727
76.6	74.2	646	55658.0	728
74.2	70.8	646	75002.0	956
70.8	67.5	548	25614.6	518
67.5	64.2	548	25614.6	518
64.2	60.9	548	25614.6	518
60.9	57.6	548	25614.6	518
57.6	54.2	548	25614.6	518
54.2	50.7	548	51914.0	717
50.7	47.1	548	53397.0	738
47.1	44.6	548	57812.0	735
44.6	42.0	548	60125.0	764
42.0	38.3	446	25571.6	752
38.3	34.7	446	25571.6	752
34.7	31.0	446	25571.6	752
31.0	27.4	446	25571.6	752
27.4	23.7	446	25571.6	752
23.7	21.1	446	44783.3	772
21.1	18.5	446	44783.3	772
18.5	16.0	446	44783.3	772
16.0	13.9	446	40202.7	574
13.9	11.8	446	40202.7	574
11.8	9.7	446	40202.7	574

Table C-2. Surface elevation, volume and surface area of run-of-the-river reservoir segments on the Columbia River between Grand Coulee Dam and Bonneville Dam

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	Volume (acre-feet)	Area (acres)
590.0	584.9	978	46717.0	734
584.9	579.9	978	46717.0	734
579.9	574.8	978	46717.0	734
574.8	569.8	978	46717.0	734
569.8	564.7	978	46717.0	734
564.7	559.7	978	46717.0	734
559.7	554.8	978	91643.0	459
554.8	549.9	978	91643.0	459
549.9	545.1	978	91643.0	459
545.1	539.2	803	33809.6	1571
539.2	533.3	803	33809.6	1571
533.3	527.4	803	33809.6	1571
527.4	521.5	803	33809.6	1571
521.5	515.6	803	33809.6	1571
515.6	505.1	719	52658.0	1731
505.1	494.7	719	52658.0	1731
494.7	484.3	719	52658.0	1731
484.3	480.8	719	52604.0	1092
480.8	477.3	719	52604.0	1092
477.3	473.7	719	52604.0	1092
473.7	466.9	619	42688.0	997
466.9	460.1	619	42688.0	997
460.1	453.4	619	42688.0	997
453.4	424.2	580	173964.0	7728
424.2	415.8	580	157110.0	5094
415.8	397.1	491	184014.0	7014
324.0	314.4	357	217147.0	9724
314.4	301.1	357	209010.0	5176
301.1	292.0	357	250113.0	4323
292.0	273.3	276	206635.0	8712
273.3	265.0	276	227752.0	9325
265.0	256.6	276	235460.0	5771
256.6	249.1	276	214530.0	4184
249.1	243.7	276	213204.0	3533
243.7	236.3	276	241671.0	3348
236.3	229.1	276	292632.0	3711
229.1	222.3	276	295188.0	4068
222.3	215.6	276	286356.0	3175
215.6	191.5	182	299532.0	8567
191.5	165.7	82	284148.0	8387
165.7	145.5	82	285538.0	9072

Table C-3. Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Hanford Reach of the Columbia River.

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
397.1	392.4	450	16.0994	0.6010	99.5337	0.2170
392.4	386.7	450	10.4826	0.6491	46.1598	0.2990
386.7	382.1	450	5.1545	0.6966	10.8665	0.3940
382.1	377.4	450	35.6628	0.5364	798.8506	0.0730
377.4	371.6	450	21.0634	0.6032	292.7820	0.1990
371.6	364.4	450	29.5736	0.5646	374.7002	0.1290
364.4	358.3	450	16.1049	0.6030	91.6599	0.2060
358.3	353.6	450	14.0921	0.6336	82.1749	0.2670
353.6	346.3	450	41.4013	0.5346	940.1158	0.0690
346.3	339.5	450	1.4800	0.8018	1.0554	0.6050
339.5	333.6	450	60.2303	0.5596	664.3698	0.1190
333.6	329.4	450	26.2448	0.6340	129.2020	0.2680
329.4	324.0	450	94.4921	0.5597	1585.1760	0.1190

Table C-4. Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Snake River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
139.3	135.1	727	1.3734	0.8395	1219.8387	0.0527
135.1	130.0	714	0.2497	0.9333	46.2064	0.2693
130.0	124.9	700	4.5948	0.6862	33.9653	0.268
124.9	120.5	683	13.1143	0.6076	183.1265	0.1204
120.5	114.9	675	65.4102	0.4679	31.1958	0.2663
114.9	111.2	657	0.4202	0.8997	27.1063	0.3282
111.2	105.0	650	86.6362	0.4700	495.2805	0.0575
105.0	100.0	634	3.6130	0.7320	20.2729	0.3588
100.0	95.0	616	0.4122	0.8931	153.2817	0.1676
95.0	90.0	604	33.1126	0.5367	482.9053	0.0617
90.0	85.0	591	11.5359	0.6274	411.3987	0.0815
85.0	80.0	578	15.8938	0.6009	546.5048	0.0624
80.0	75.0	564	2.8035	0.7458	949.4666	0.0317
75.0	70.0	550	0.0371	1.0999	21.1241	0.3705
70.0	65.0	536	34.9564	0.5409	41.3614	0.2837
65.0	64.1	519	13.6486	0.6047	262.7923	0.1151
64.1	60.0	519	13.6486	0.6047	262.7923	0.1151
60.0	55.0	497	2.8014	0.7103	1.7944	0.5102
55.0	50.0	484	12.9094	0.6103	274.3042	0.1084
50.0	45.2	470	5.7302	0.6849	625.4147	0.0585
45.2	39.6	456	11.7427	0.6265	675.5304	0.0599
39.6	34.7	440	0.8356	0.8345	674.6927	0.0508
34.7	29.7	426	12.8951	0.6176	561.4941	0.0676
29.7	24.9	413	10.0577	0.6458	215.5004	0.1681
24.9	20.5	401	99.3539	0.4457	144.4178	0.1517
20.5	15.0	389	1336.7927	0.2308	217.4554	0.0779
15.0	10.1	371	7.3970	0.6552	528.2647	0.0806
10.1	5.1	356	14.7118	0.6003	738.0669	0.0397
5.1	0.0	344	3.1882	0.7395	236.7204	0.1704

Table C-5. Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Columbia River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
596.1	593.3	1000	2.6338	0.7352	18.0219	0.3374
593.0	590.0	980	2.6338	0.7352	18.0219	0.3374
590.0	582.3	957	0.7270	0.8120	71.3679	0.223
582.3	574.6	950	8.0662	0.6987	1099.0507	0.0508
574.6	568.0	942	0.7307	0.8405	33.2019	0.2845
568.0	560.5	931	3.0785	0.7268	41.2264	0.2468
560.5	556.1	923	78.9803	0.4911	106.4525	0.1716
556.1	550.5	915	13.6134	0.5940	77.8754	0.1894
550.5	543.5	875	0.9457	0.7627	28.1202	0.2858
543.5	536.0	795	241.4499	0.3980	569.5330	0.045
536.0	528.5	787	3.6436	0.7084	37.3599	0.2799
528.5	524.1	773	3.6436	0.7084	37.3599	0.2799
524.1	521.0	761	4.3695	0.7015	30.4070	0.3061
521.0	516.6	755	21.8397	0.5685	62.3113	0.2475
516.6	513.5	742	8.9346	0.6667	204.5063	0.1391
513.5	509.6	740	8.9346	0.6667	204.5063	0.1391
509.6	504.0	737	50.0570	0.5268	373.5261	0.0727
504.0	496.7	727	0.6773	0.8267	1.3620	0.5177
496.7	489.3	716	30.0809	0.5715	141.8256	0.1773
489.3	481.0	702	2.1101	0.7502	24.0741	0.3206
481.0	474.5	682	4.5249	0.7103	29.2092	0.3209
474.5	472.8	645	18.5590	0.6002	381.3065	0.1018
472.8	465.3	638	18.5590	0.6002	381.3065	0.1018
465.3	461.1	622	98.3723	0.4602	601.2292	0.0486
461.1	456.9	596	98.3723	0.4602	601.2292	0.0486
456.9	452.1	591	46.2149	0.4941	52.8461	0.1974
452.1	447.2	550	19.1734	0.5999	97.9604	0.2138
447.2	441.3	541	9.3458	0.6566	249.7985	0.1548
441.3	435.8	533	34.7602	0.5667	650.6808	0.087
435.8	427.5	529	177.3813	0.4614	1239.7894	0.0537
427.5	419.2	523	116.7612	0.5084	2121.0964	0.0471
419.2	415.0	514	116.7612	0.5084	2121.0964	0.0471
415.0	412.2	490	304.7172	0.3970	481.3450	0.1025
412.2	409.5	472	304.7172	0.3970	481.3450	0.1025
409.5	407.1	468	71.4189	0.5197	589.8682	0.1286
407.1	403.1	459	71.4189	0.5197	589.8682	0.1286
403.1	397.3	454	93.4202	0.5409	434.8807	0.1681
397.1	392.4	450	16.0994	0.6010	99.5337	0.2172
392.4	386.7	450	10.4826	0.6491	46.1598	0.299
386.7	382.1	450	5.1545	0.6966	10.8665	0.3948
382.1	377.4	450	35.6628	0.5364	798.8506	0.0731
377.4	371.6	450	21.0634	0.6032	292.7820	0.1991
371.6	364.4	450	29.5736	0.5646	374.7002	0.1297
364.4	358.3	450	16.1049	0.6030	91.6599	0.2066
358.3	353.6	450	14.0921	0.6336	82.1749	0.2678

Table C-5 (continued). Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Columbia River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
353.6	346.3	450	41.4013	0.5346	940.1158	0.0693
346.3	339.5	450	1.4800	0.8018	1.0554	0.605
339.5	333.6	450	60.2303	0.5596	664.3698	0.1195
333.6	329.4	450	26.2448	0.6340	129.2020	0.2683
329.4	324.0	450	94.4921	0.5597	1585.1760	0.1194
324.0	319.0	319	8.1919	0.6777	15.5388	0.4047
319.0	315.0	319	8.1919	0.6777	15.5388	0.4047
315.0	310.0	311	8.1919	0.6777	15.5388	0.4047
310.0	305.0	304	3.6979	0.7577	4.8827	0.5124
305.0	300.0	298	0.1471	0.9998	50.1033	0.3363
300.0	295.0	290	0.3042	0.9383	32.7658	0.3662
295.0	290.0	279	5.5772	0.7054	16.3420	0.4116
290.0	285.0	267	7.3793	0.6946	20.1463	0.3881
285.0	280.0	260	1.2465	0.8363	184.3870	0.2182
280.0	275.0	256	222.7504	0.4407	2.3317	0.5328
275.0	270.0	244	1.0377	0.8121	0.6808	0.6399
270.0	265.0	237	0.2465	0.9716	7.7394	0.5002
265.0	260.0	230	12.4667	0.6535	161.5547	0.2115
260.0	255.0	224	0.2303	0.9490	21.5631	0.3816
255.0	250.0	221	22.1718	0.6173	88.7304	0.2695
250.0	245.0	216	10.2468	0.6940	178.6500	0.2291
245.0	240.0	212	0.0527	1.0805	19.4272	0.3972
240.0	235.0	209	12.0935	0.6696	71.3909	0.2919
235.0	230.0	206	524.6108	0.3843	935.8895	0.07
230.0	225.0	199	1.6655	0.7684	476.1715	0.1207
225.0	220.0	181	3.5737	0.7293	260.5219	0.1704
220.0	215.0	176	1878.4895	0.2832	1367.9987	0.0409
215.0	210.0	164	7.9771	0.6813	141.3714	0.2097
210.0	205.0	160	27.2777	0.5970	634.6995	0.105
205.0	200.0	148	41.1050	0.5813	9.0817	0.4604
200.0	195.0	140	41.1050	0.5813	9.0817	0.4604
195.0	190.0	137	2244.5522	0.2914	680.3396	0.095
190.0	185.0	76	0.9950	0.8306	58.5292	0.2722
185.0	180.0	75	5.2198	0.7354	745.1066	0.0994
180.0	175.0	73	1800.4440	0.3021	106.4071	0.2303
175.0	170.0	72	227.3922	0.4594	121.2100	0.2483
170.0	165.0	69	27.8419	0.6190	574.8106	0.1414
165.0	160.0	65	21.0582	0.6312	959.7112	0.1039
160.0	155.0	62	21.0582	0.6312	959.7112	0.1039
155.0	150.0	59	2.7886	0.7433	302.9572	0.1456
150.0	146.1	48	2.7886	0.7433	302.9572	0.1456
146.1	140.0	24	0.3407	0.8362	1.1586	0.5184

Appendix D

Statistical Analysis Of Simulation Results

The statistical analyses were performed in this study to quantify levels of uncertainty associated with simulation results. Means and standard deviations of the difference between observed and simulated temperatures were computed for the entire simulation period and for each two-month period for the duration of the simulation (01/01/1990 – 12/31/1994). The results are given in Tables D-1 through D-9. An analysis of the regression of observed results on simulated results was also performed. In the regression analysis, the linear relationship is constrained to pass through the origin of the coordinates at (X=0, Y=0) as shown in Figures D-1 through D-9. The results of the regression are shown Table D-10.

Certain statistics are also generated as part of the parameter estimation process. These include the theoretical and sample variance of the innovations process Figures D-10 through D-18 and the innovations process (Equation 12) (Figures D-19 through D-27).

When reviewing these statistics it is important to keep in mind that the means and standard deviations of the difference between observed and simulated are based on state estimates using the model in the *prediction* mode. That is, the state estimates from the model do not depend on prior observations. The statistics generated by the parameter estimation process are a result of using the model in the *filtering* mode. This means that the innovations sequence, the difference between observed and the systems update prior to filtering, is a function of previous observations and state estimates. In addition, the parameter estimation process attempts to estimates the bias in the observations.

Table D-1. Mean and standard deviation of the difference between observed and simulated temperatures at Wells Dam (Columbia River Mile 515.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	-0.028	0.510
May-June	0.035	0.802
July-August	-0.136	0.529
September-October	0.494	0.488
November-December	---	--
Entire Year	0.009	0.677

Table D-2. Mean and standard deviation of the difference between observed and simulated temperatures at Priest Rapids Dam (Columbia River Mile 397.1) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.320	0.999
May-June	-0.623	0.895
July-August	-0.499	0.880
September-October	0.855	0.433
November-December	---	--
Entire Year	-0.277	1.012

Table D-3. Mean and standard deviation of the difference between observed and simulated temperatures at McNary Dam (Columbia River Mile 292.0) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.940	0.929
May-June	0.749	1.194
July-August	0.884	1.335
September-October	1.653	1.027
November-December	---	--
Entire Year	0.983	1.236

Table D-4. Mean and standard deviation of the difference between observed and simulated temperatures at John Day Dam (Columbia River Mile 215.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	0.580	1.309
March-April	1.273	0.730
May-June	0.283	0.924
July-August	0.288	0.986
September-October	0.9425	0.646
November-December	---	---
Entire Year	0.560	1.021

Table D-5. Mean and standard deviation of the difference between observed and simulated temperatures at Bonneville Dam (Columbia River Mile 215.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.909	1.002
May-June	0.413	1.248
July-August	-0.382	1.423
September-October	0.524	0.868
November-December	---	---
Entire Year	0.241	1.306

Table D-6. Mean and standard deviation of the difference between observed and simulated temperatures at Bonneville Dam (Columbia River Mile 215.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.909	1.002
May-June	0.413	1.248
July-August	-0.382	1.423
September-October	0.524	0.868
November-December	---	---
Entire Year	0.241	1.306

Table D-7. Mean and standard deviation of the difference between observed and simulated temperatures at Lower Granite Dam (Snake River Mile 107.5) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.052	1.388
May-June	-0.040	1.363
July-August	1.136	1.120
September-October	0.409	1.076
November-December	-0.133	0.203
Entire Year	0.588	1.320

Table D-7. Mean and standard deviation of the difference between observed and simulated temperatures at Little Goose Dam (Snake River Mile 70.3) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.086	1.144
May-June	-0.196	1.167
July-August	0.131	1.532
September-October	-0.228	1.436
November-December	---	---
Entire Year	0.048	1.420

Table D-8. Mean and standard deviation of the difference between observed and simulated temperatures at Lower Monumental Dam (Snake River Mile 41.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.543	0.900
May-June	0.027	0.884
July-August	-0.067	1.269
September-October	-0.036	0.933
November-December	---	---
Entire Year	0.124	1.187

Table D-9. Mean and standard deviation of the difference between observed and simulated temperatures at Ice Harbor Dam (Columbia River Mile 9.7) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.784	1.021
May-June	0.155	0.888
July-August	0.192	1.190
September-October	0.625	1.093
November-December	---	---
Entire Year	0.407	1.202

Table D-10. Slope of line and R^2 for regression of observed temperature data on simulated results in the Columbia and Snake rivers for the period 1990-1994. Regression was constrained to force the straight line to pass through the origin (X (simulated)=0, Y (observed)=0).

Measurement Site	Slope of Line	R^2
Wells Dam	0.995	0.973
Priest Rapids Dam	0.999	0.940
McNary Dam	1.004	0.929
John Day Dam	0.995	0.976
Bonnevile Dam	0.995	0.904
Lower Granite Dam	1.005	0.931
Little Goose Dam	0.997	0.907
Lower Monumental Dam	0.992	0.923
Ice Harbor Dam	0.998	0.929

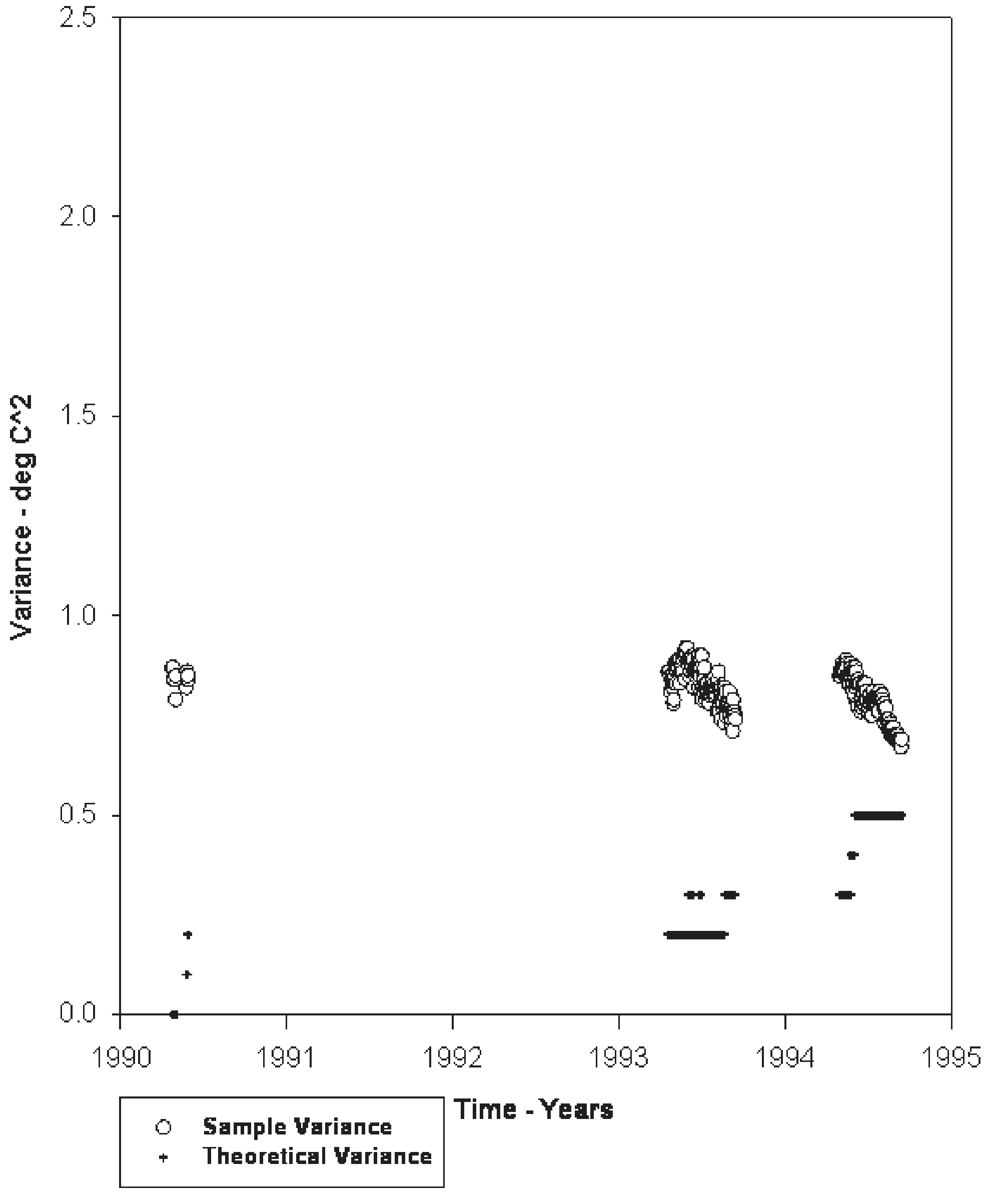

Figure D-10. Theoretical and sample variance of innovations sequence at Wells Dam - 1990-1995

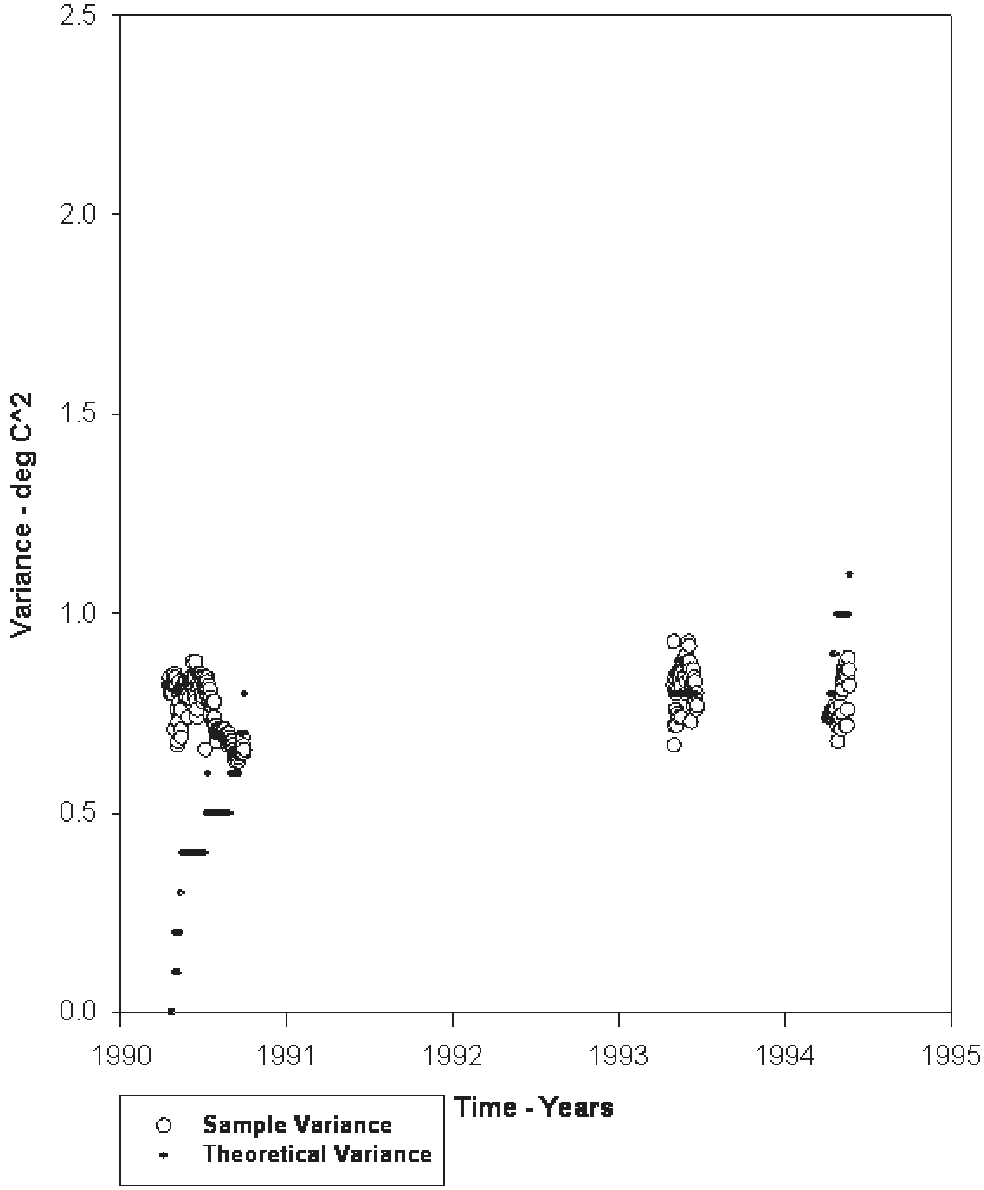

Figure D-11. Theoretical and sample variance of innovations sequence at Priest Rapids Dam - 1990-1995

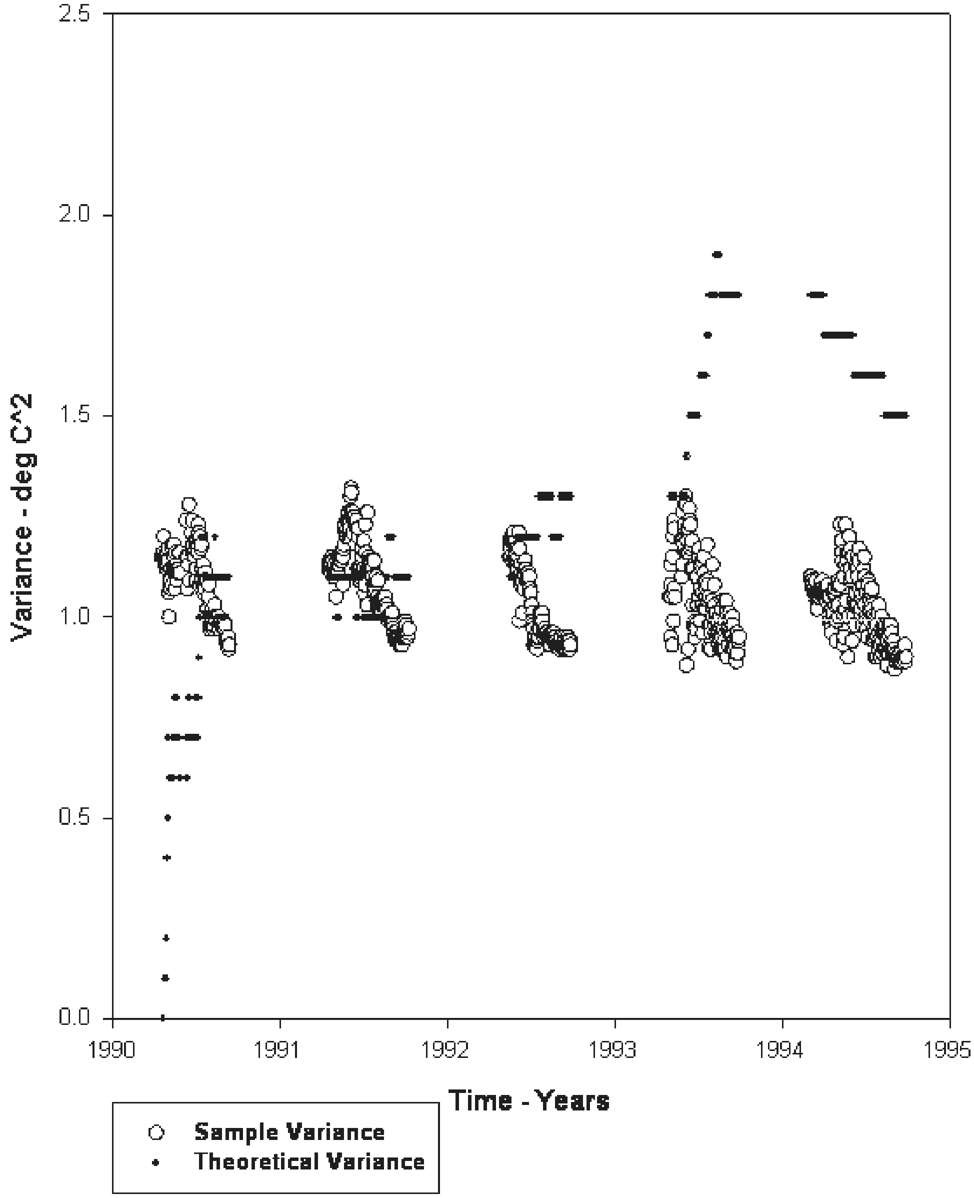

Figure D-12. Theoretical and sample variance of innovations sequence at McNary Dam - 1990-1995

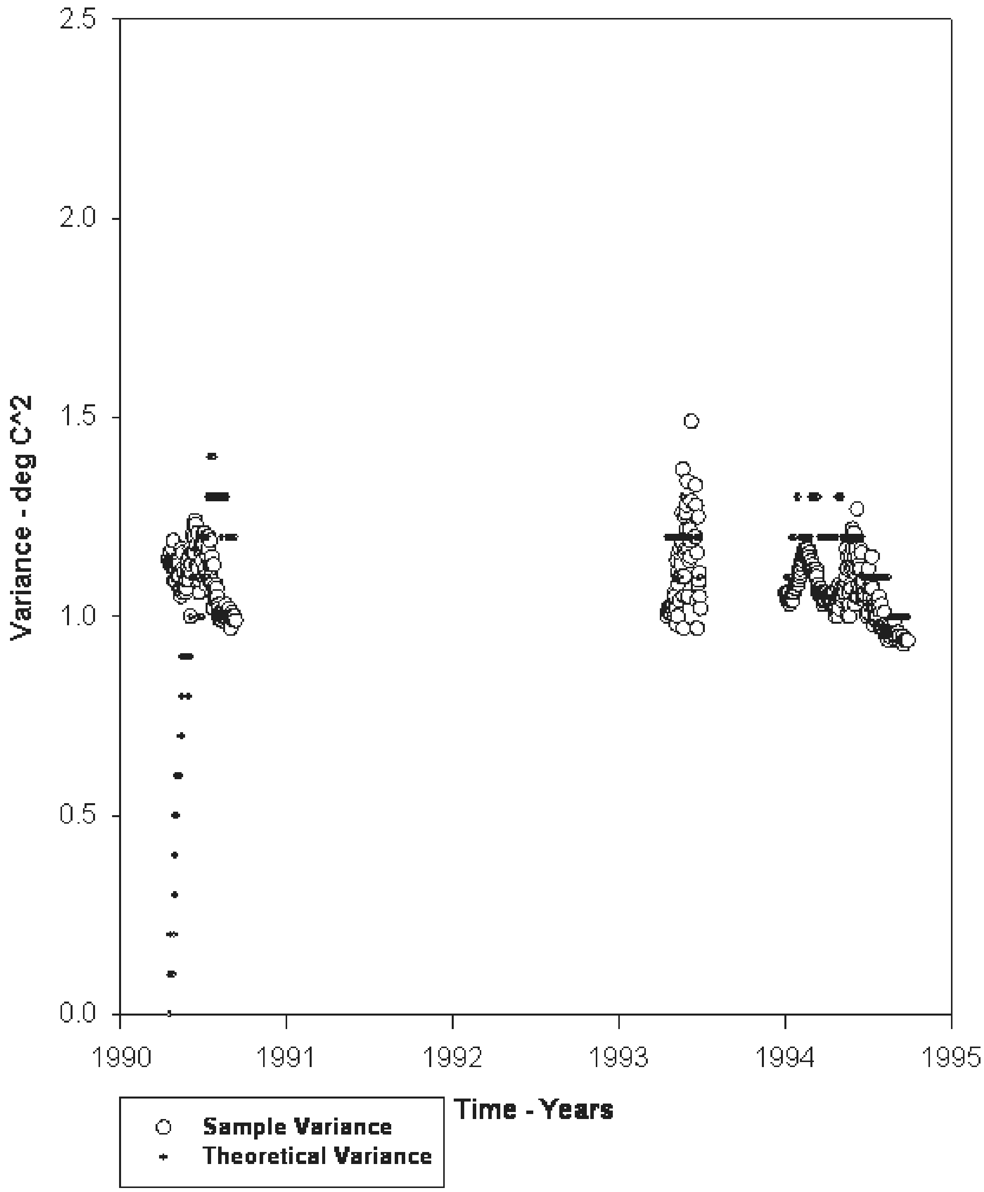

Figure D-13. Theoretical and sample variance of innovations sequence at John Day Dam - 1990-1995

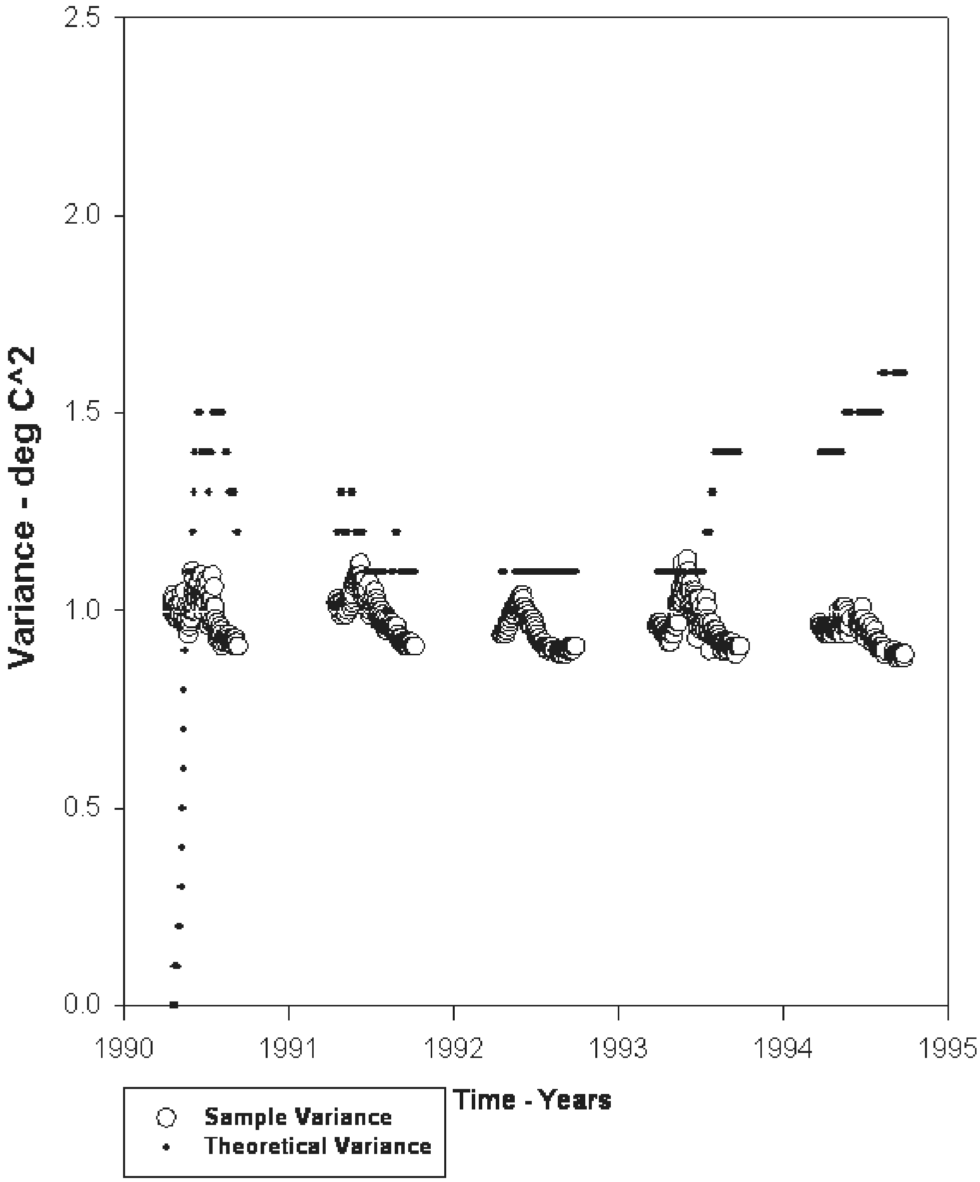

Figure D-14. Theoretical and sample variance of innovations sequence at Bonneville Dam - 1990-1995

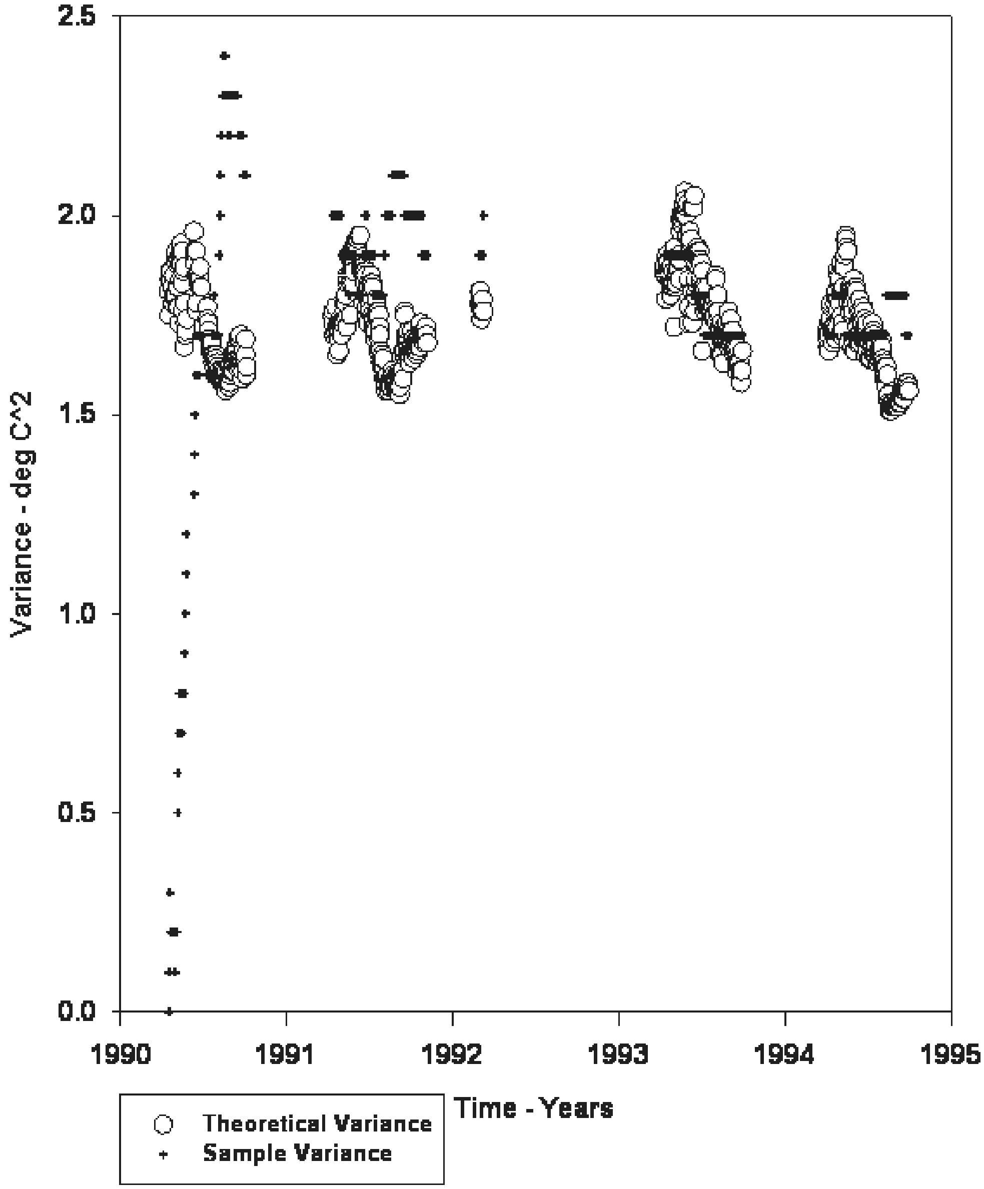

Figure D-15. Theoretical and sample variance of innovations sequence at Lower Granite Dam

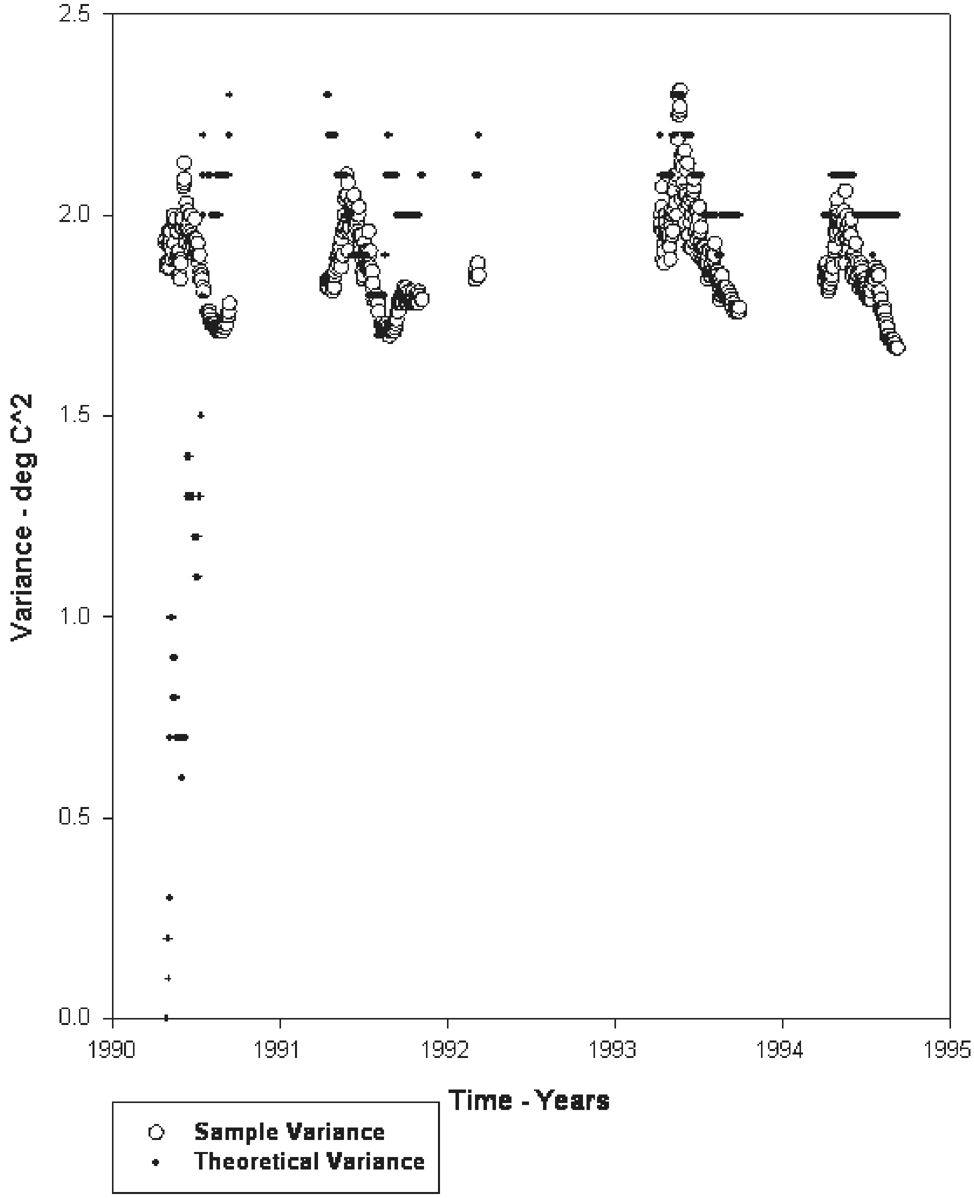

Figure D-16. Theoretical and sample variance of innovations sequence at Little Goose Dam - 1990-1995

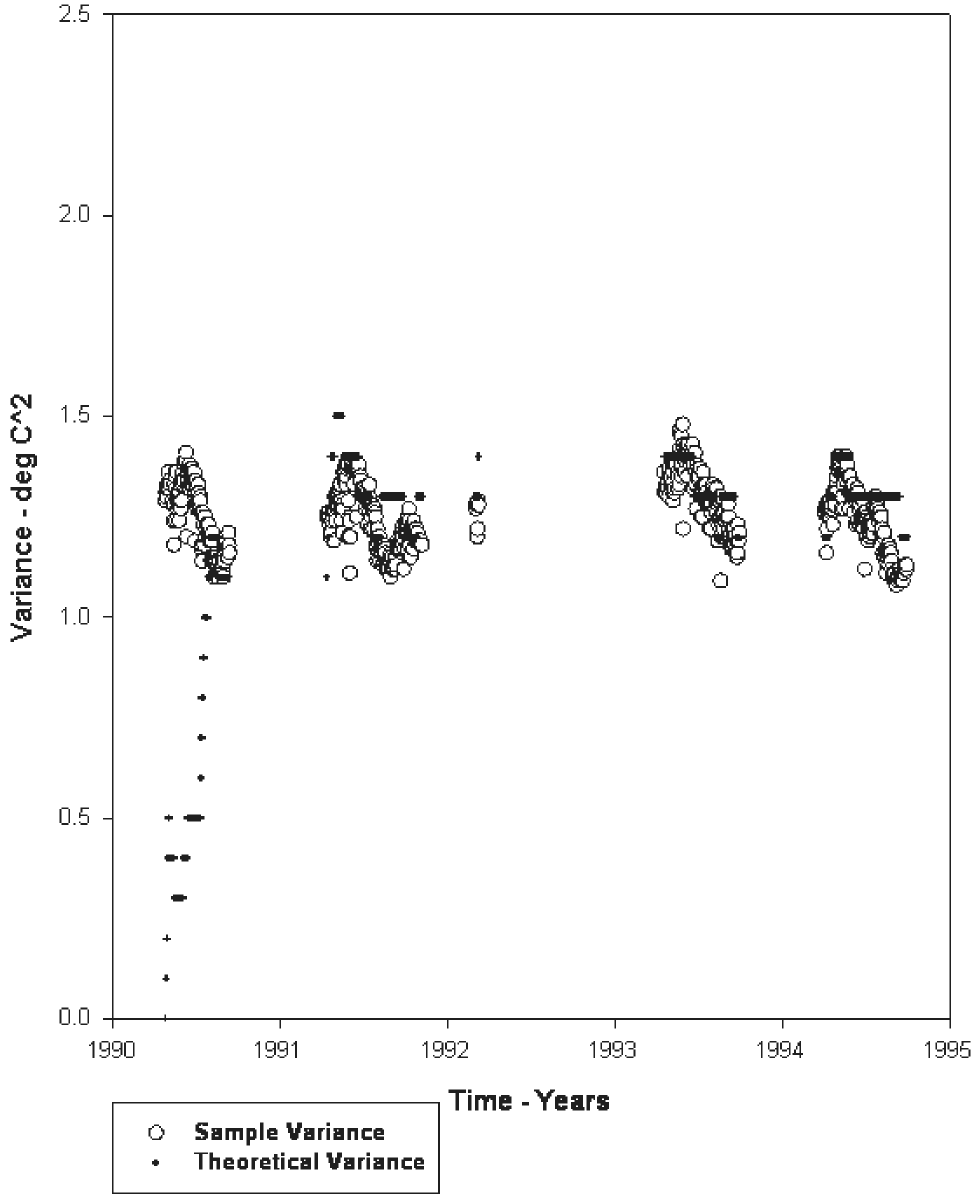

Figure D-17.
Theoretical and sample variance of innovations sequence at Lower Monumental Dam - 1990-1995

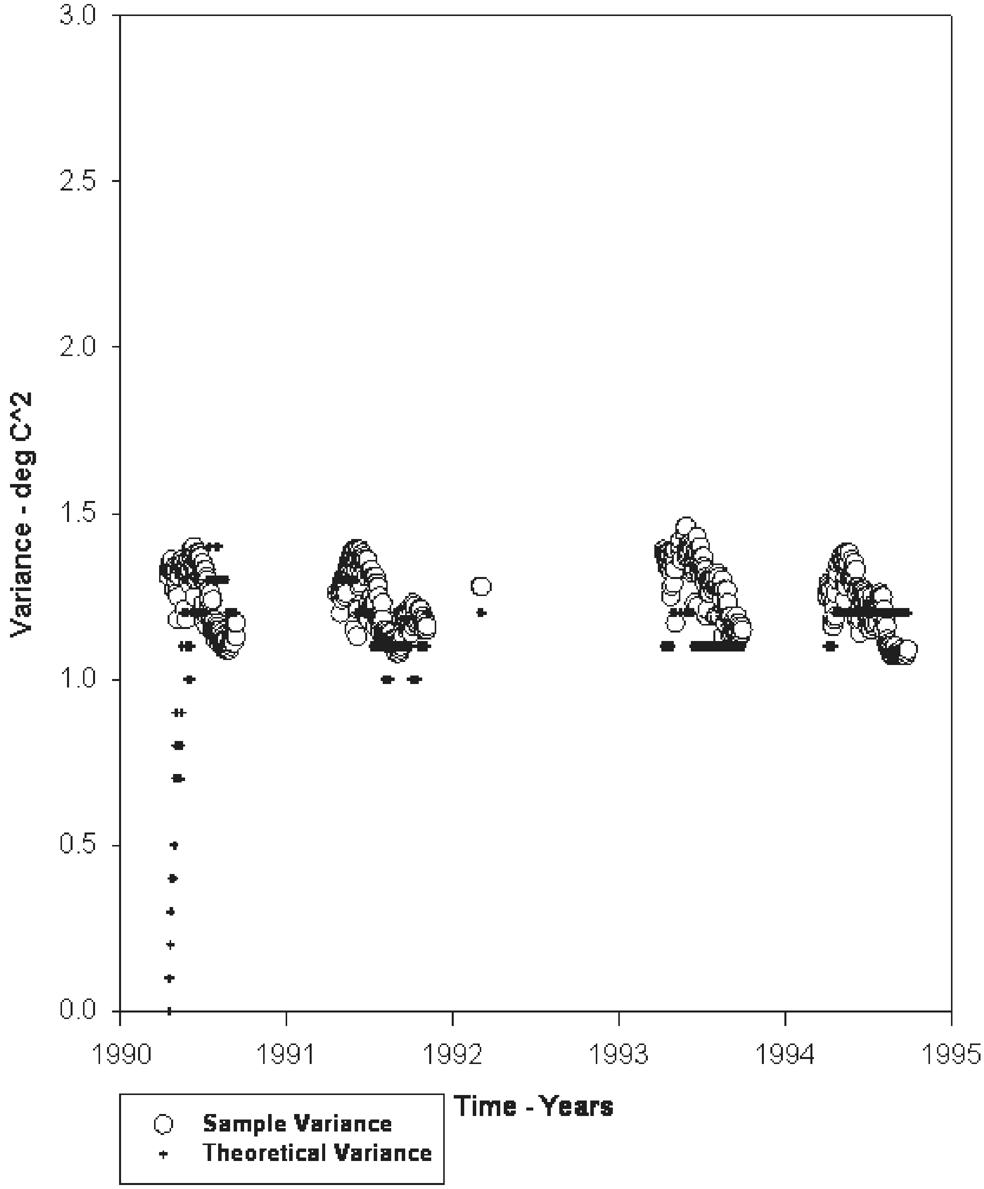

Figure D-18. Theoretical and sample variance of innovations sequence at Ice Harbor Dam - 1990-1995

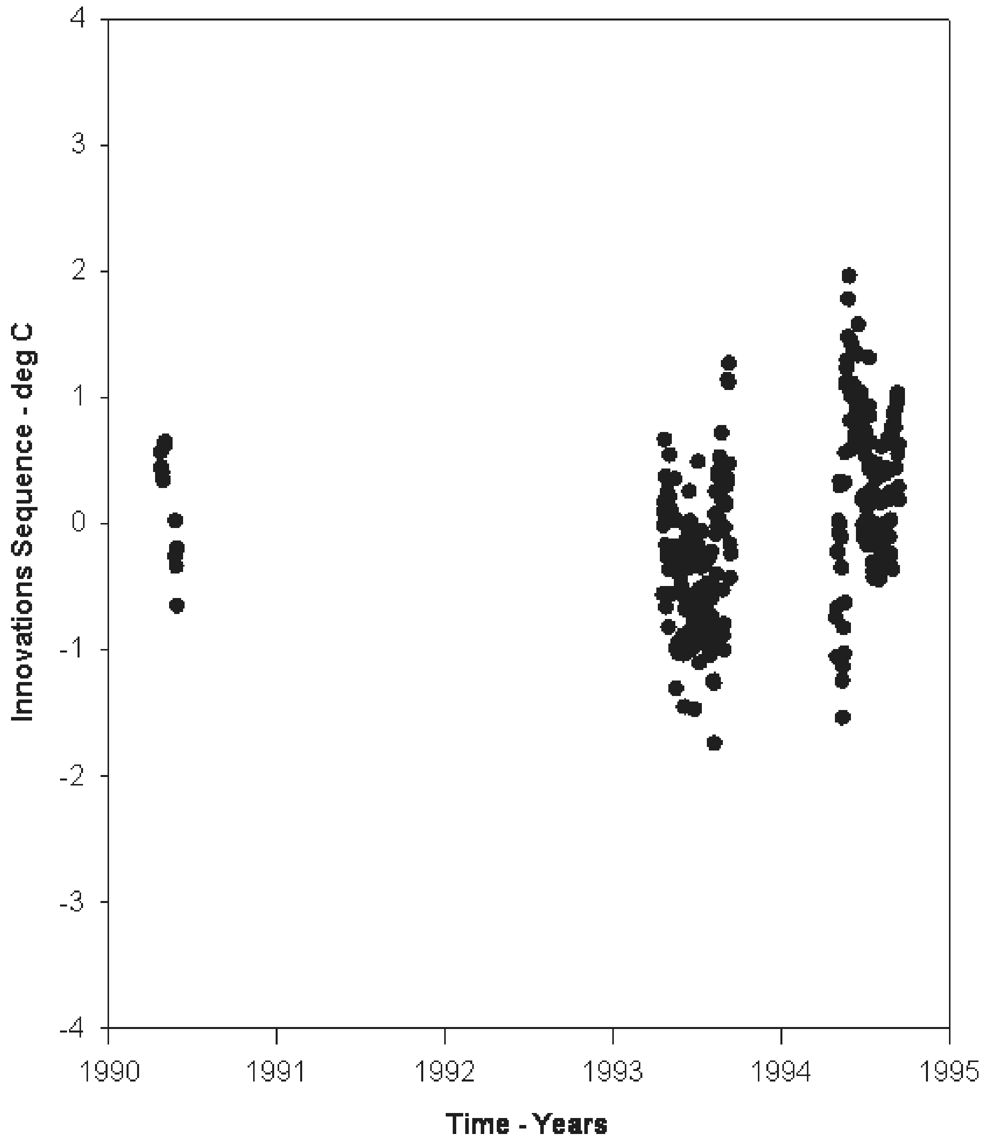

Figure D-19. Innovations sequence for Wells Dam - 1990-1995

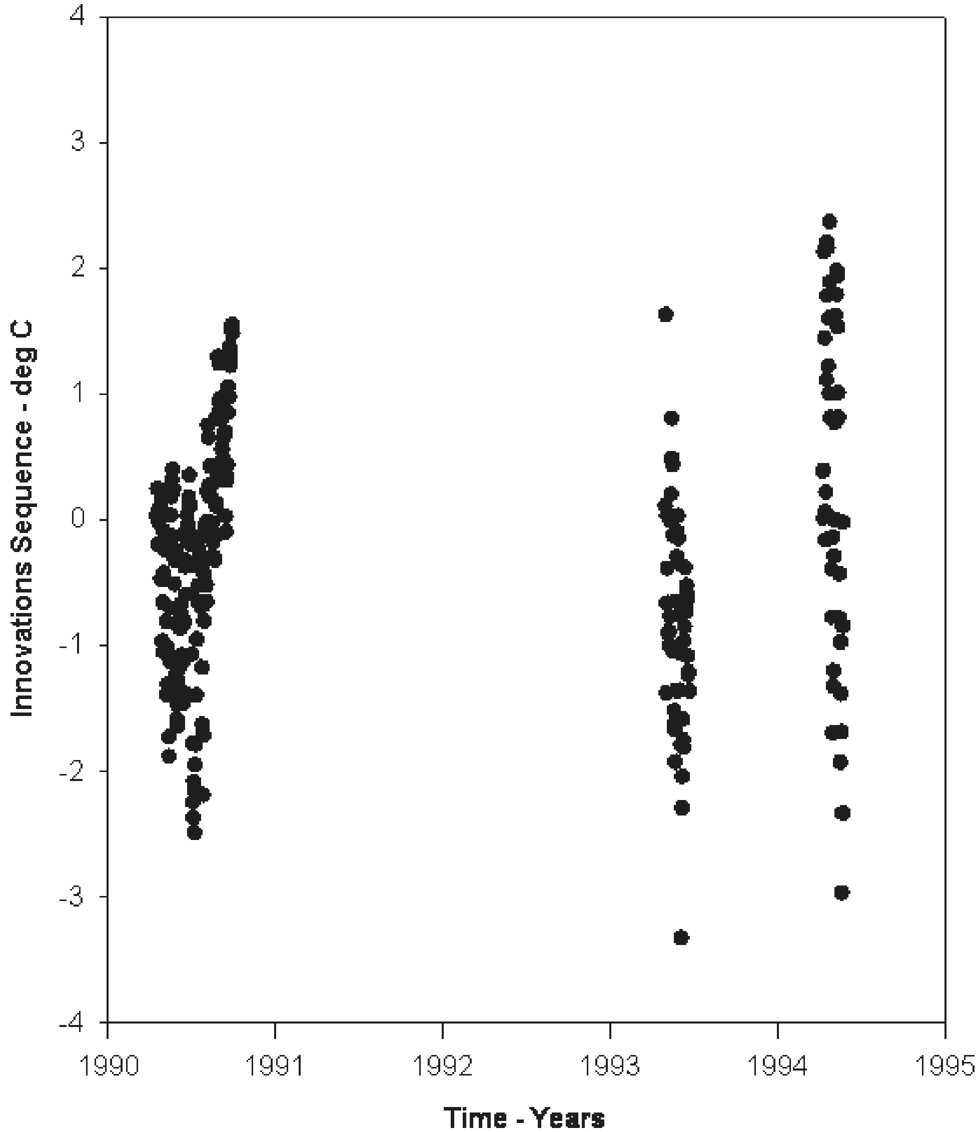

Figure D-20. Innovations sequence for Priest Rapids Dam - 1990-1995

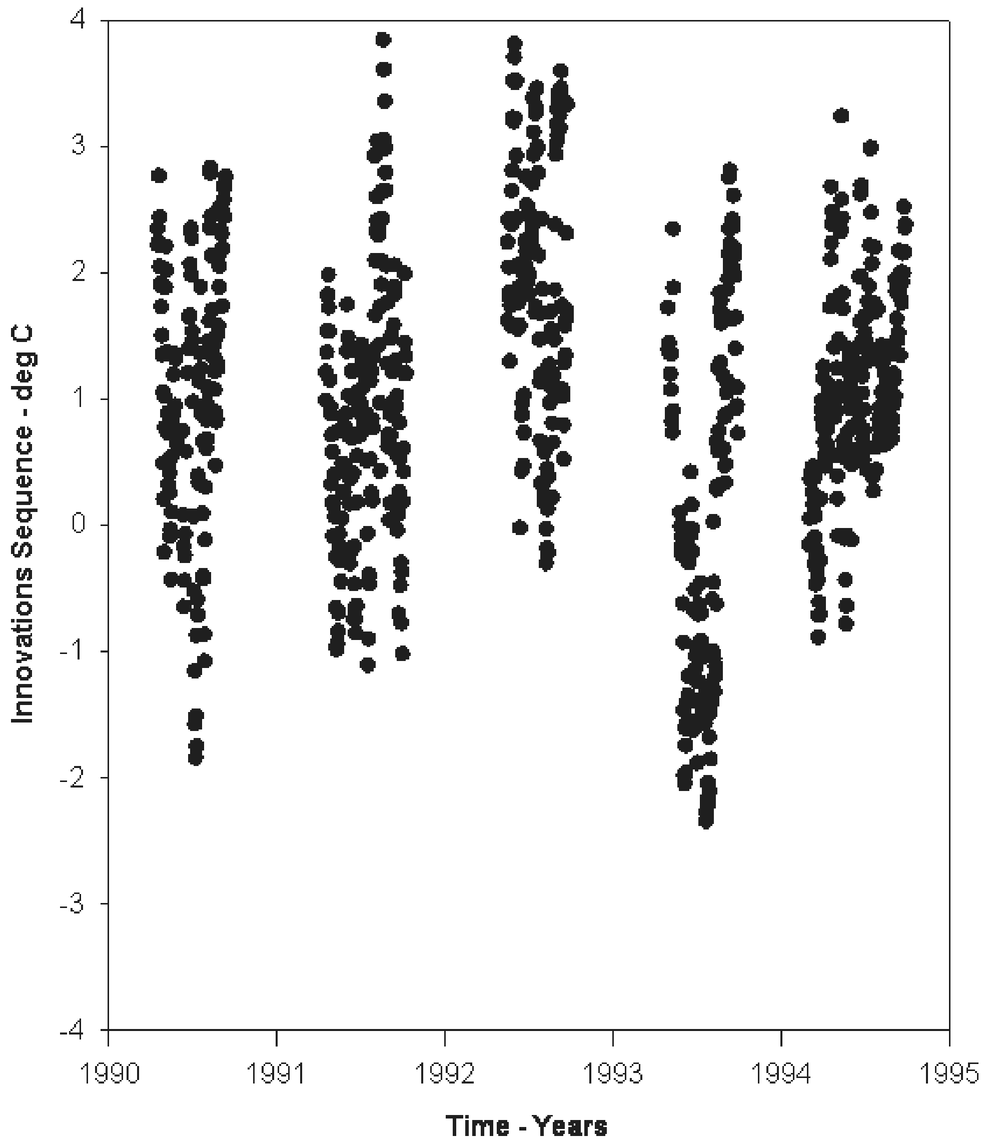

Figure D-21. Innovations sequence for McNary Dam - 1990-1995

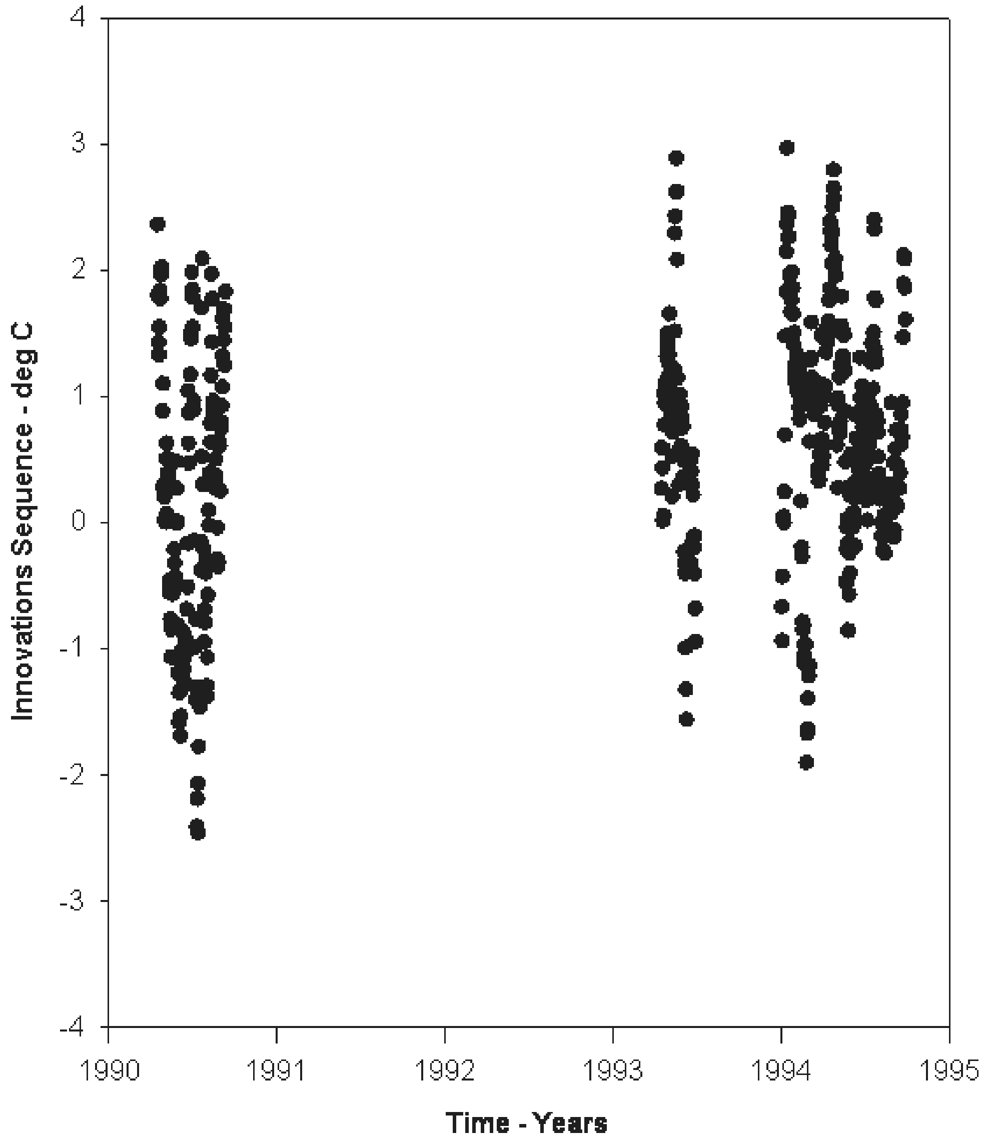

Figure D-22. Innovations sequence for John Day Dam - 1990-1995

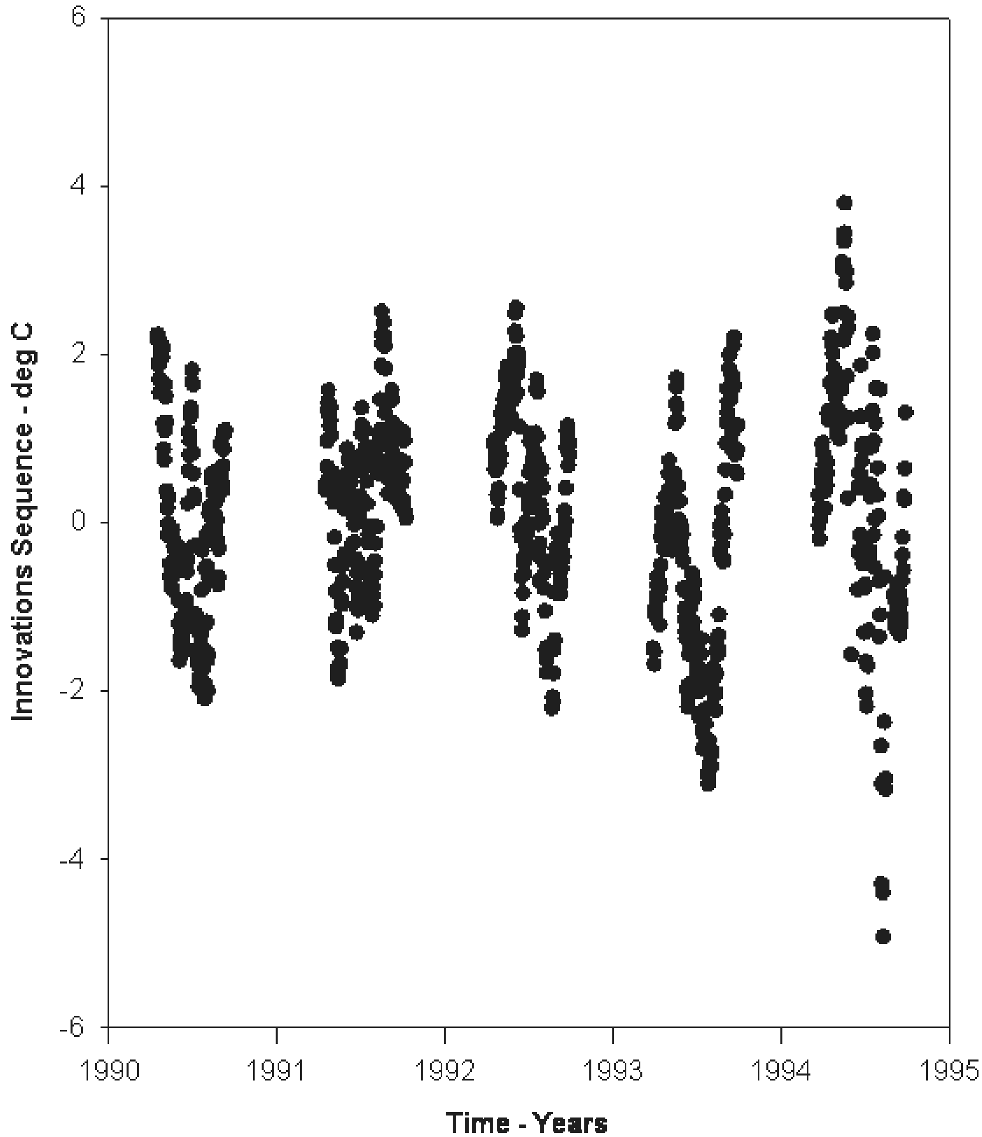

Figure D-23. Innovations sequence for Bonneville Dam - 1990-1995

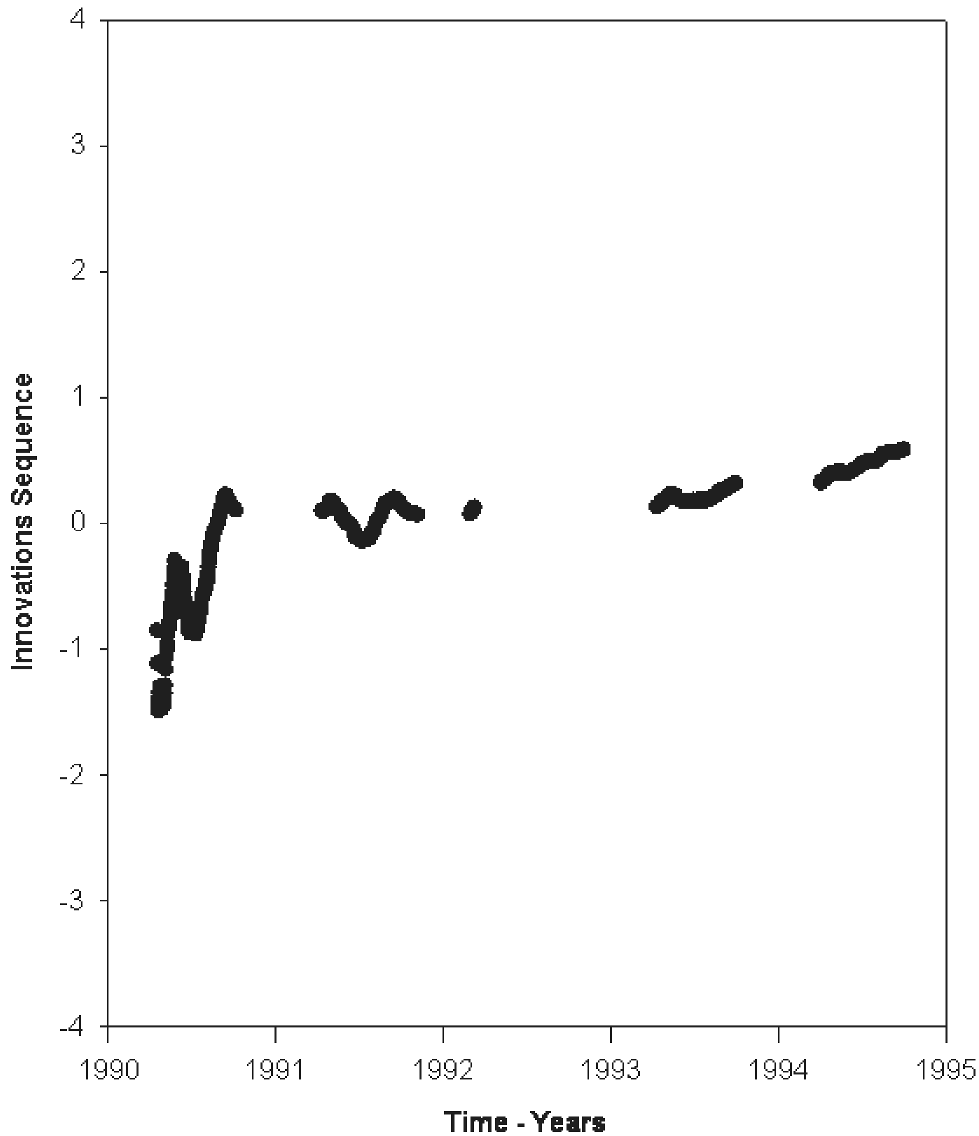

Figure D-24. Innovations sequence at Lower Granite Dam - 1990-1994

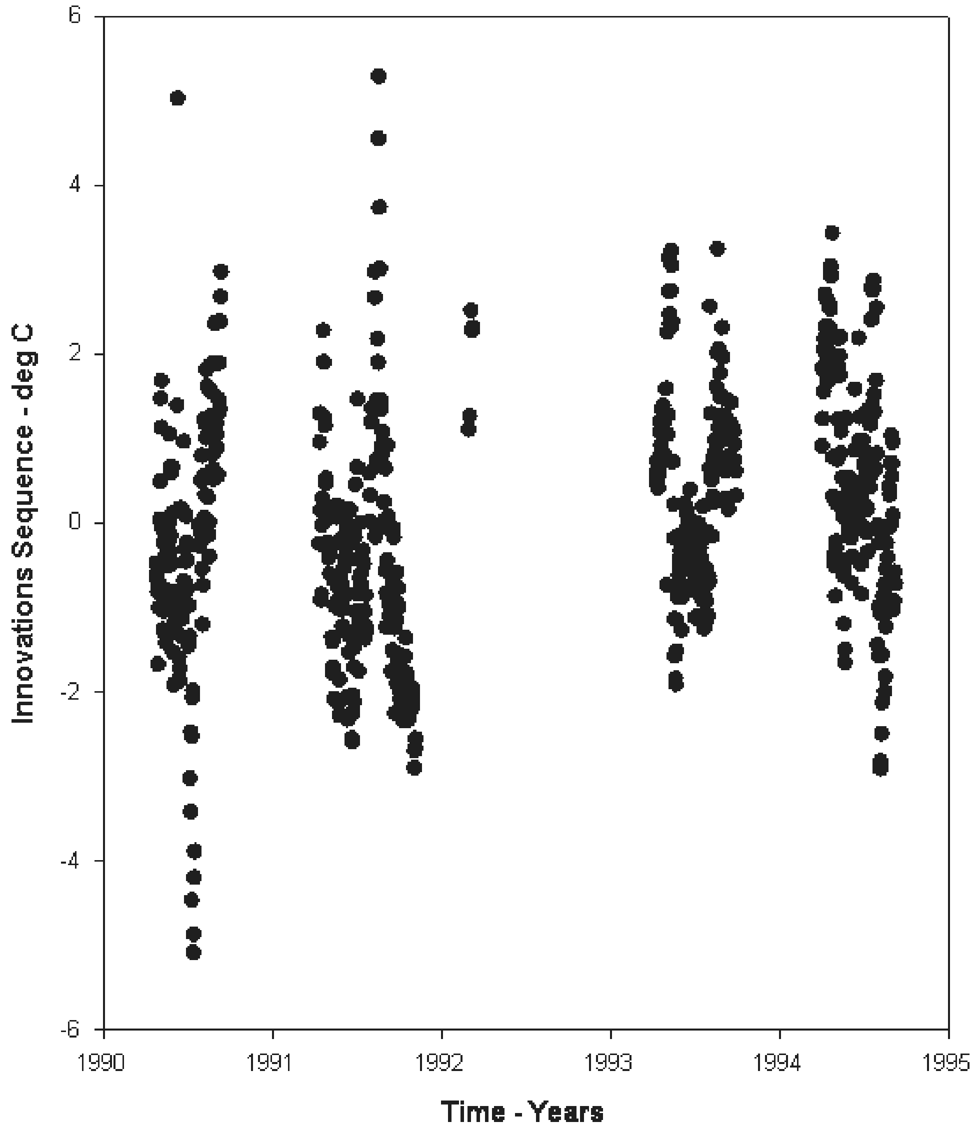

Figure D-25. Innovations sequence for Little Goose Dam - 1990-1995

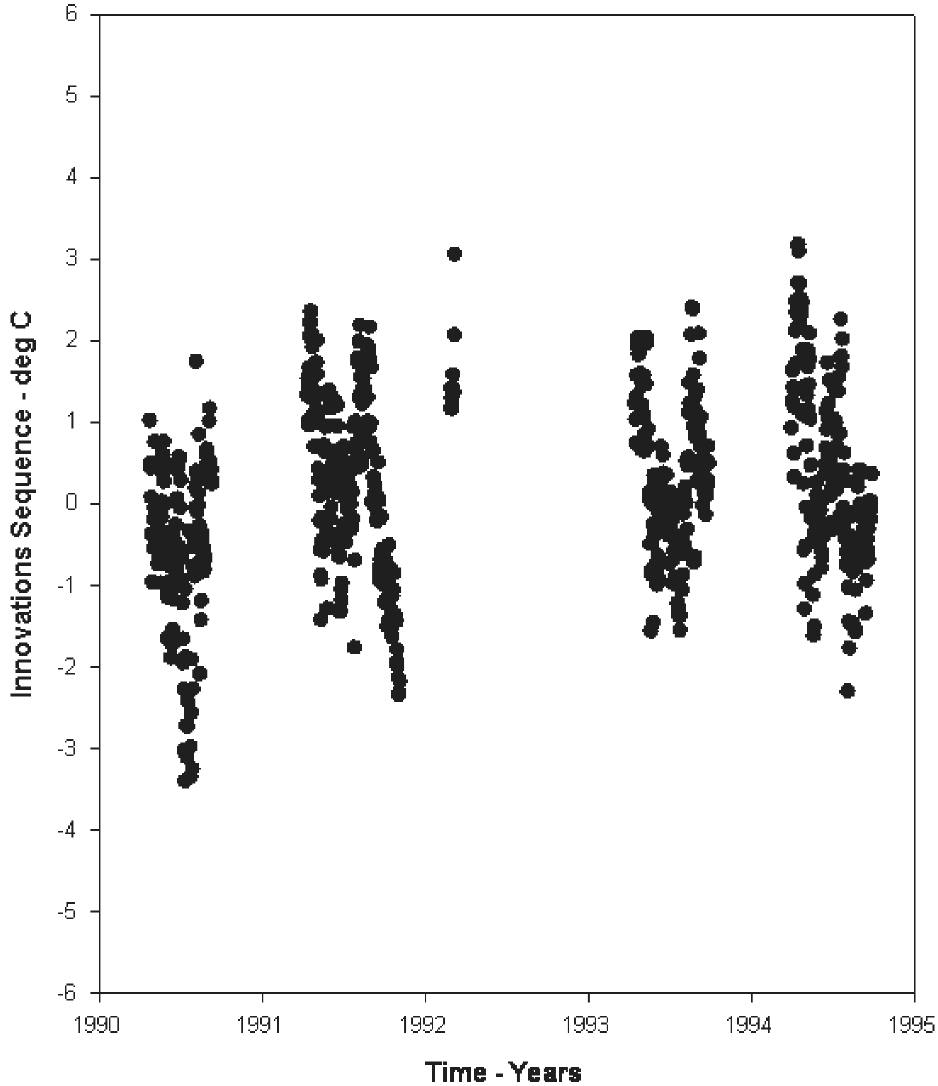

Figure D-26. Innovations sequence for Lower Monumental Dam - 1990-1995

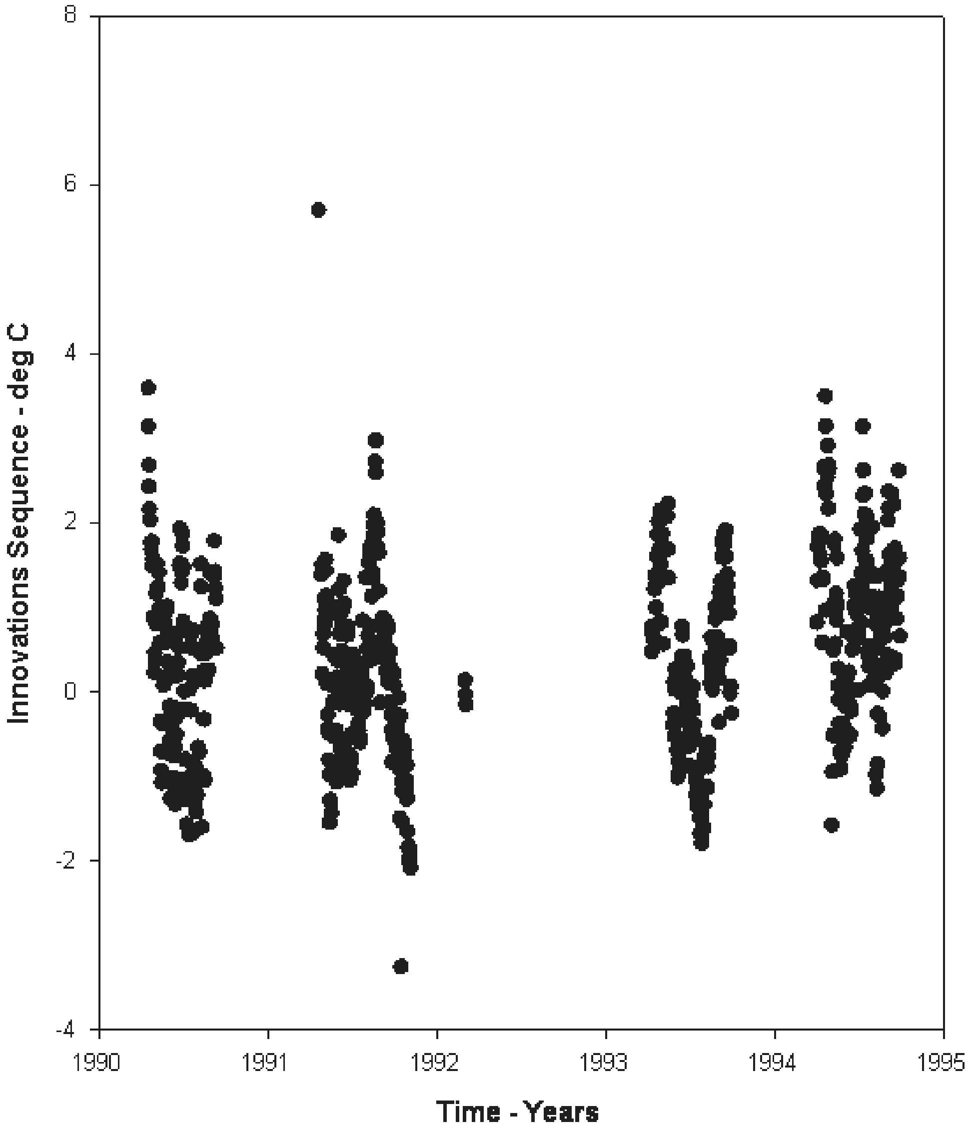

Figure D-27. Innovations sequence for Ice Harbor Dam - 1990-1995